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A comprehensive review on biomass cookstoves and a systematic approach for modern cookstove design

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ABSTRACT

Improved biomass cookstoves has been a topic of research for more than 40 years, but still 2.6 billion people cook over an open biomass fire. A large volume of information on the biomass cookstoves though widely scattered, is available in the literature. This paper gives a comprehensive review of the available literature on biomass cookstoves. The review covers a detailed discussion on various aspects of biomass cookstoves: historic overview, performance characteristics, cooking accessories, testing protocols, barriers to dissemination and adoption, and future pathways. In addition, comparison of energy and emissions performance for different biomass cookstoves is given. Data is obtained from reliable sources, arranged logically, plotted carefully, and analyzed to draw some interesting conclusions. Learning from the review and comparison made, is used to propose a novel "Systematic Approach for Modern Cookstove Design".

Contents

Abbreviations: TSF, three stone fire; ICS, improved cookstove; IAP, indoor air pollution; CO, carbon monoxide; PM, particulate matter; ARC, Aprovecho Research Center; NPIC, Indian National Programme on Improved Chulhas; NISP, Chinese National Improved Stove Programme; MNRE, Ministry of New and Renewable Energy; EPA, Environmental Protection Agency; CDM, clean development mechanism; NBCI, National Biomass Cook stove Initiative; ABS, advanced biomass stove; VITA, Volunteers in Technical Assistance; TLUD, top lift updraft stove; TEG, thermo-electric generator; WBT, water boiling test; CWBT, comparative water boiling test; CCT, controlled cooking test; HTP, heterogeneous testing protocol; KPT, kitchen performance test; SUMs, stove use monitors; UFT, uncontrolled field test; UCT, uncontrolled cooking test; BCT, burning cycle test; CDT, cookstove durability testing; CFD, computational fluid dynamics; NGOs, non-governmental organizations; ISO, International Standards Organization; IWA, International Workshop Agreement; TOP, tiers of performance

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1. Introduction

In the era of spacecrafts, computers, and electronic gadgets, about 2.6 billion people do not have access to clean cooking facilities; and if predictions are believed the approximately same number will still be so in 2030 [1]. About 1.6 million people die prematurely per year; from indoor air pollution, resulting from solid-fuel cooking; causing more than 2% of the whole world diseases (4% in the poorest nations) [2]. Cooking with solid biofuels also has a significant global impact on, greenhouse gas and black carbon emissions, accounting for 1–3% of all human generated global warming [3]. Venkataraman et al. concludes that, the solid biofuel combustion is the dominant source of global black carbon emissions, with as much as 42% of total black carbon emissions in India [4]. The heavy dependence on biomass resources and their inefficient utilization can be a significant source of deforestation and resulting climate change, as observed in studies conducted independently, in six Tanzanian cities [5] and three urban regions of Ethiopia [6].

As a solution to these global problems, energy and emission efficient ICSs can reduce: diseases, by decreasing indoor air pollution (IAP); time and cost of obtaining fuel; risk of violence against women and children gathering fuel in conflict areas; consequent climate change and deforestation. Hence, in the "Biomass Cookstoves Technical Meeting" held on January 2011, the expert team on cookstove technologies set new benchmarks for ICS: "at least 90% emissions reductions and 50% fuel savings over baseline technology (three-stone fire)" [7].

Currently more than 160 cook stove programmes are running in the world, across different nations [8]. Since 1970s, the laboratory, the field, and the policy aspects of biomass cookstoves have been studied under ICS projects by many renowned researchers like Samuel Baldwin [9], Barnes, Smith [10,11], Prasad [12], and Bryden [13]. Numerous studies conducted by such researchers, helped build a database regarding various issues related to cookstoves such as design, development, testing, materials, dissemination and field performance. Unfortunately, much of the literature is widely spread, and it is hard to get a good outline of the subject. This review paper is an effort to address the need for concise and simplified discourse; on scientific knowledge related to biomass cookstoves.

2. Biomass cookstoves

"Biomass cookstove" is a physical structure that contains air-fuel combustion for heat release, and subsequently, directs the heat of combustion towards a cooking target (pot/pan/griddle). Besides cooking, stoves provide useful energy for space/water heating, in-house lighting, fish/meat smoking, and grain/flour roasting. The same device in many cultures, serves more than one of these functions. Modern cookstoves guarantee more than a plain fire; features such as high efficiency, low emissions, and safety of the user. According to the wide range of food habits, socio-cultural factors, and fuel type available; there exist, no of cookstove designs across the world whether traditional or improved.

2.1. Historic overview of biomass cookstoves

Cookstoves are as old as the human history. They have evolved in numerous shapes and sizes, made up of varied materials, and adapted to different cultures and cuisines, with the advent of time.

2.1.1. Early history (time immemorial—1950)

Evidence is present, for the biomass fuel use within the caves of Peking man as early as 500,000 years ago [14]. From ancient times, while styles and methods of cooking have developed, the "archetypal" stove, which is today's "traditional stove" or the "three-stone fire (TSF)" has been as it was formed, for around 12,000 years now [15]. The "archetypal" stove remains predominant in the entire world up to the 18th century, and in the rural areas of many developing countries even to date. It was by the Industrial Revolution of the 18th and 19th centuries that the modern cooking technologies began. A book published in 1802 (London): "Essays, Political, Economical, and Philosophical" by Count Rumford, has descriptions of research on fireplaces, ovens and boilers [16].

2.1.2. The recent past (1950–2000)

In 1950s, the Gandhian organizations in India initiate the process of biomass cookstove development, labeled the "classic phase" by Kirk Smith; focusing mainly on the reduction of the smoke exposure in kitchens, with the introduction of chimney stoves [16,17]. However, no scientific research and development of the ICS took place until the late 1970s or the early 1980s.

It was the 1970s' oil crisis, which made the world pay attention to the energy issues; and as an answer to the fuel wood crisis and consequent deforestation, ICS received attention. Westhoff [15] identifies the period between the 1970 and the 1980 as marking the "first wave" of improved stove development. Then predictions to the effect that, high biofuel use will cause deforestation and escalated poverty; motivated the "first wave" or "energy phase" or "first phase" of stove development. The focus of designers in "energy phase" was on achieving fuel savings, through increased efficiencies, with smoke reduction being a secondary issue [9,17]. It was during this period, that improved cookstove movement began in the Africa at Sahel, after the severe drought of the late 1970s. The Guatemala earthquake of 1976 in Central America introduced the ICSs to the region, especially, the "Lorena stove" [15]. The famous Aprovecho Research Center (ARC) came to existence in 1976 with the aim of facilitating the research, development, and dissemination of the clean cookstove technologies.

During 1980–1990, when the issues associated with the use of traditional stoves such as women-empowerment, enhancement of livelihoods, and natural resource conservation gained international recognition, "phoenix" period or "second phase" of stove development started [17]. Superior stove designs based on scientific studies, steadily evolved during the mid 1980s. During this phase, a strong technical base for the cookstoves was laid because of heat transfer and fluid mechanics studies [9,12]; systematic testing and design procedures were also gradually established [18,19]. A large number of ICS models were developed and disseminated during this phase; with stove programmes in India and China being two major events. However Barnes et al. [10] conclude that the stove programmes executed between the 1980s and the early 1990s, were not much successful.

The "third phase", of stove development, which began at the start of 1990s, shifted researchers' focus on the consumer needs, such as smoke reduction in kitchens, user's safety, and convenience in the stove use. The "third phase" combines additional environmental issues with the previous motivations of fuel savings. Single pot stoves without chimney or artisan made metal stoves, were the major stove types developed and disseminated during this period.

Amongst important events during the recent past was the "Indian National Programme on Improved Chulhas" (NPIC), first as a demonstration programme from 1983 to 1984, then on a full-fledged scale in 1985 [20,21]. It resulted in the development of more than 60 stove designs and Over 35 million stoves dissemination [22,23]. Another impact programme during this period was "The Chinese National Improved Stoves Programme" (NISP), which has been addressed as the "World's largest publicly financed initiative to improve stoves" [24]. Between 1982 and 1992, the NISP introduced some 129 million improved biomass and coal stoves, in rural areas [25]. With more than 100 million cookstoves still used, NISP is one of the successful stove programmes [26].

2.1.3. The new millennium (2000—to date)

In 2002, Ministry of New and Renewable Energy (MNRE) India deemed NPIC a failure, stopping funding to the programme, and passing the responsibility to the states [20,23]. However, after more than a decade of decline, the interest in household energy (and hence ICS) emerged again at the international level. In 2002, at the "World Summit on Sustainable Development" held in Johannesburg, the "U.S. Environmental Protection Agency" (EPA) launched the "Partnership for Clean Indoor Air", to address the environmental health risk faced by people using traditional biomass fuels indoors. In another favorable development, the "Clean Development Mechanism" (CDM), in February 2008, included cookstove programmes in their agenda under "smaller decentralized projects", by revising the programmatic guidelines [27]. Because of this, about 14 cookstove projects are registered as "Programmes of Activities" with CDM as on May 2013 [28]. In December 2009, rejuvenating the efforts of providing clean cooking services to its people, the Government of India launched, "The National Biomass Cook stove Initiative" (NBCI) with the goal "Our aim is to achieve the quality of energy services from cookstoves comparable to that from other clean energy sources such as LPG" [22]. In September 2010, the U.S. Department of State and EPA helped launch "The Global Alliance for Clean Cookstoves" at New York. United Nations Foundation, comprising over 600 partners, is leading the alliance with the goal of creating the global market for energy and emissions efficiency cookstoves, to solve multiple issues associated with the cookstove use. The Alliance's goal calls for 100 million homes to adopt "clean and efficient stoves and fuels by 2020".

Health and environmental concerns, in addition to fuel efficiency are the main motivations of present day stove programmes. However, as with the earlier phases, the majority of these have been unable to scale up significantly [29]. Even today, only 40% of the people in developing countries have access to modern fuels for cooking [30]. Out of the people relying on solid-fuels for cooking in

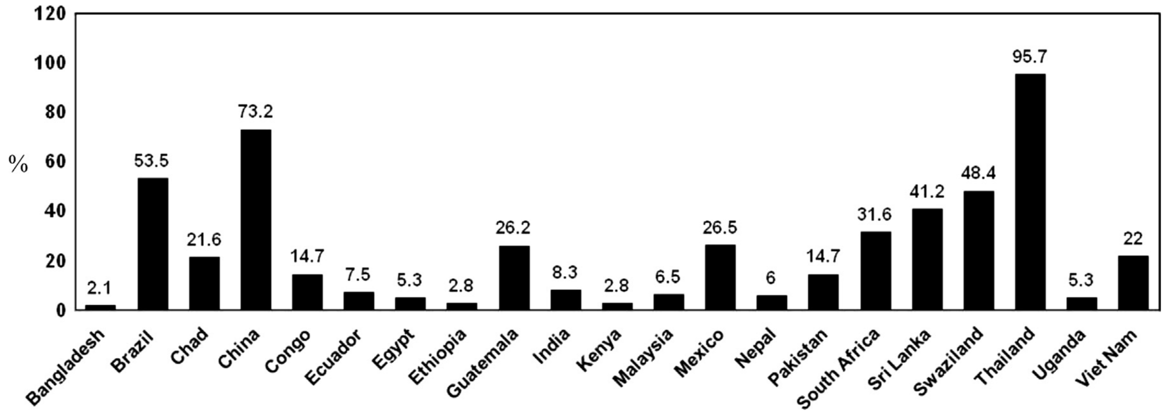

Fig. 1. Percentage of people having access to ICS in some of the developing countries.*
Data Source: The energy access situation in developing countries: a review focusing on the least developed countries and sub-Saharan Africa [30].

developing countries, only 30% have access to ICSs [30]. In most of these nations, access to ICSs is available to less than one-fourth of the people using solid-fuels (Fig. 1). However, access is much higher in some countries such as China, Thailand, and Brazil [30]. Instead of mixed results obtained so far; some 166 million ICSs are still in use, as an inheritance of the efforts of all cookstove initiatives of the past [26].

2.2. Classification of biomass cookstoves

Fig. 2 shows a diagrammatic representation of biomass cookstoves classification.

2.2.1. Traditional versus improved and advanced cookstoves

2.2.1.1. Traditional cookstoves. Traditional stoves have developed over thousands of years, according to local culture and food practices. These stoves are least costly, and the users are familiar with their operation; and hence are widely accepted in society. Traditional stoves are of two types, the first being “three-stone fire”, a fire built directly on the ground using three stones, and placing a cooking target at the top. The main disadvantage of TSF is its low efficiency, however, did perform better compared to some of the ICS in lab tests [31,32]. Laboratory investigations for TSF have shown moderate time to boil, high fuel consumption, high CO and PM emissions, and low thermal efficiency of about 20% [31,32]; beside this, TSF is the least safe stove, mainly because of exposed fire [31].

The second type of traditional stove is “Built-in stove” or “Mud-stove”, which is a modification of the TSF. A “Built-in Stove” is a semi-permanent mud structure that encloses fire from at least three directions, other than the ground itself. Examples include *chullah, angithi,* and *haroo in* India [33]; traditional *mogogo* and *Jiko* in Africa; and *Plancha* in central and south America [15,34,35]. Built-in stoves provide some advantages over TSF: enclosed fire and hence reduction in radiation losses; restricted fuel feeding at a time, thereby limiting fuel use; and enclosed gas path, which lessens the entrainment of ambient air. However, reducing the amount of primary air supply to the fuel can result in incomplete combustion, leading to increase in IAP. The mud stove testing in the laboratory have shown fast boiling, high CO/PM emissions, average thermal efficiency of about 29%, and moderate safety rating, mainly, because of enclosed fire [31].

2.2.1.2. Improved cookstoves. The “Improved Cookstove” is a cookstove designed using certain scientific principles, to assist better combustion and heat transfer, for improving emissions and efficiency performance; it may also utilize modern construction materials for serving the purpose. The goal of an ICS design is to improve upon the shortcomings of the traditional stoves, while still ensuring lower cost and ease of use. A few common design strategies are placing a fuel-grate under the burning fuel, provision of low density and specific heat walls for enclosing fire, provision of a short internal chimney above the fire, designing properly sized channels for forcing heat into the pot, and use of insulation. There exists a number of ICSs able to reduce emissions by 40–75%, increase fuel efficiency by almost 30% [31,32] and reduce global warming potential up to 40–60% [36]. The most famous categories of ICS are “Rocket” stoves and Gasifier stoves.

2.2.1.3. Advanced biomass stoves. Advanced biomass stoves (ABS) are recently developed, factory-manufactured cookstoves, based on modern technical and product development research; and standards that include higher efficiency, lower emissions, better safety and enhanced durability [22,26]. These next-generation cookstoves commonly have advanced features, such as induced or forced airflow for cleaner burning. ABS, enables factory-based production, undergoes thorough quality testing, and hence increases the possibility of accurate reproduction of the design in all the stoves. Although current ABS shows significant emissions reductions over traditional stoves, LPG-like emission levels are yet to reach [22]. Currently, there are two broad categories of ABSs available, Gasifier stoves with two-stage combustion and the improved “Rocket” stoves with one-stage combustion. An example of “Rocket” stove type ABS are “Envirofit International's Family of Rocket Stoves” claiming to reduce fuel use by 60%, CO emissions by 60%, and black carbon by 40%. Another example is the ‘StoveTec’ from ARC which claims to use 40–50% less fuel, about half the cooking time, and emitting 50–75% less smoke as compared to TSF [26]. Gasifier type ABS models include “Oorja” and “Philips” stoves (India) [33,37,38].

2.2.2. Natural draft versus forced draft cookstoves

Nearly all the earlier domestic cookstoves (Traditional and Improved) were free convection driven. Free convective stoves even now are inevitable because of low-cost and ease of manufacturing. However, the most promising among ICSs are forced draft or fan-operated stoves. Stoves equipped with fans create high-velocity air jets that mix fuel, air, and flame. Cookstoves with fans not only reduce emissions through improved combustion, but also improve heat transfer to the cooking vessel.

While most stoves were of free convective type, Reed and Larson [39] built a fan based stove in 1996 from an earlier version described in La Fontaine and Reed [40]. Initially, these stoves were economically unaffordable, partly due to the high cost of the fan

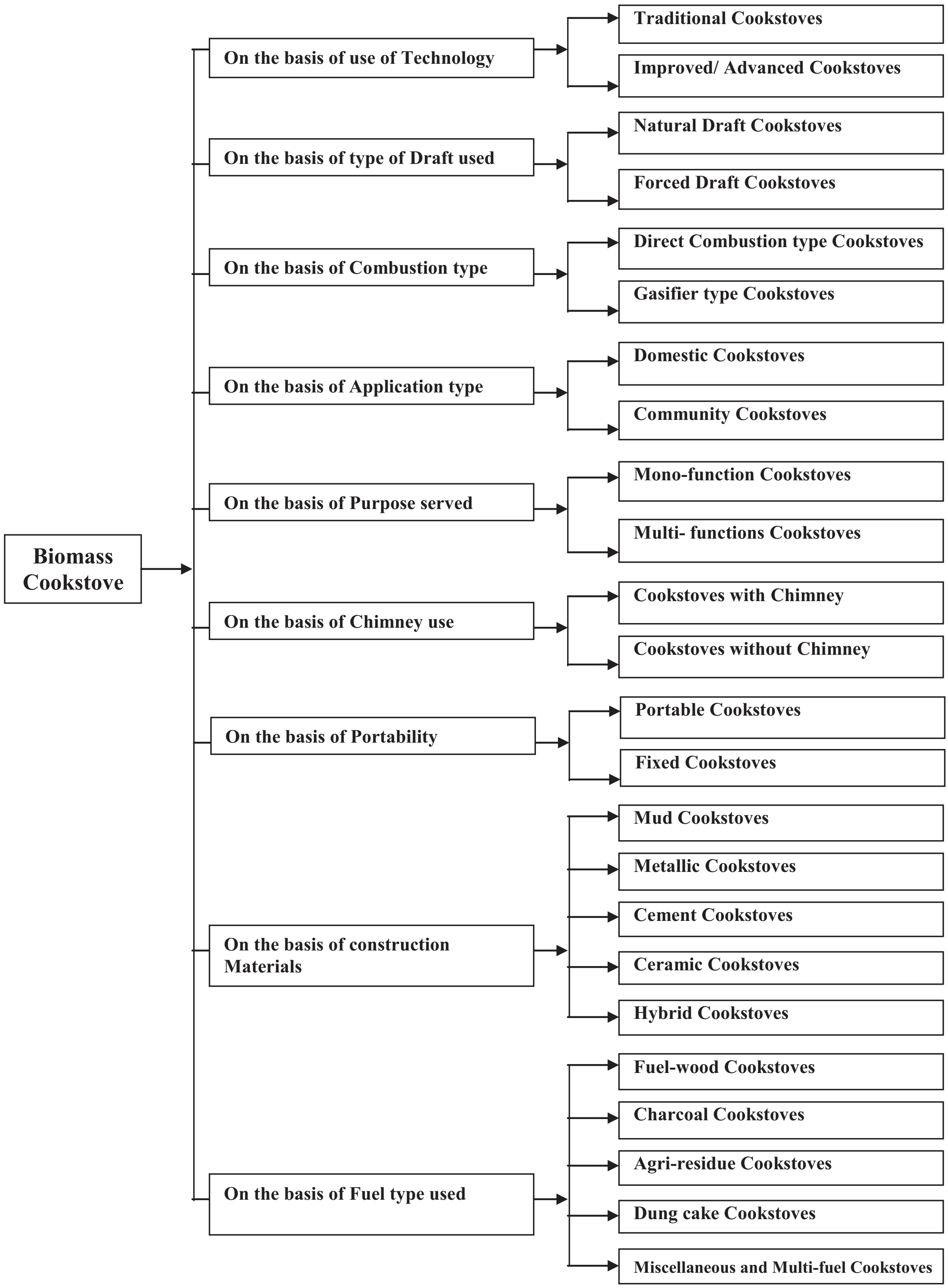

Fig. 2. Classification of biomass cookstoves.

and the power to operate the fan; however, these problems solves with the availability of computer-based fans at relatively low price and use of the thermo-electric generator. In studies performed by ARC, the forced draft stoves in comparison to natural draft stoves consumed on average 37% less fuel, emit 80% less CO and negligible PM [31].

Both, "Rocket" and Gasifier stoves use a fan. Some fan operated "Rocket" stove has shown very good efficiency and emission performance [41]; particularly, a "side feed fan stove" by ARC [42]. A study performed by Witt [43] on fan stoves: "Gusto Wood Flame stove", "Tom Reed Woodgas", and "the Witt Alpha Prototype", indicates on average reduction in fuel use by 40%; in CO by 75% and in PM by about 90%; as compared to TSF. In Gasifier fan stove category, we have "Oorja" and "Philips" stoves from India [33,37,38]. Some drawbacks of existing fan-operated stoves are poor controllability, longer time to ignite, inability to perform long

unattended cooking, need of electric supply/battery and high capital cost.

2.2.3. Direct combustion type versus gasifier type cookstoves

2.2.3.1. Direct combustion type cookstoves. Combustion is the process, where the fuel burns with air to release chemical energy stored in it. The majority of the stoves is a direct combustion type of stoves, where solid-fuel burns directly. The most famous amongst direct combustion stove is design of Larry Winiarski at ARC: the popular "Rocket stove" [13]. The "Rocket stove" design is available for last 30 years, and according to estimates about a half million "Rocket stoves" are in use worldwide [36]. In several studies "Rocket stoves" have proven their mettle, as the best amongst the category, and sometimes even better than Gasifier stoves [31,32,38]. Examples of "Rocket" type direct combustion stoves are "Envirofit International's Family of Rocket Stoves"; 'StoveTec' and "Side Feed Fan Stove" from ARC [26,42] (see Section 2.2.1 and Section 2.2.2). The "Gusto Wood Flame Stove" in North America is another example [43].

2.2.3.2. Gasifier type cookstoves. In the gasifier stove, combustion takes place in two stages. In the first stage, the fuel burns to release gases; in the second stage at the upper side of the stove, air mixes, and burns these gases. La Fontaine and Reed [40] in 1996 developed a free convection based Gasifier stove, 'Woodgas'; subsequently the forced convection version of it with a 3-W blower, the "Turbo Stove" [44,45]. The gasifier stoves are also available with and without fan. A quite popular Gasifier-blower type stove is "Philips" stove by Royal Philips Electronics of the Netherlands, which can burn the short piece of wood; about 10 cm in length [38]. Jetter et al. found that the "Philips model HD4010", a gasifier-blower stove, reduced CO and PM emissions in the laboratory by 90% relative to TSF [32]. Kar et al. discovered that "Philips" stove reduced black carbon emissions in the field by 77% than a traditional, mud cookstove [46]. "Philips" stoves are available with a controllable electric fan, powered by a rechargeable battery or thermo-electric generator. Another famous version of the forced draft gasifier stove is "Oorja" with high efficiency over 35% and low CO emissions [38]. "Oorja" is available only in rechargeable battery version.

Natural draft versions of gasifier stoves include "Vesto" (Swaziland) [47], "Champion", "Karve" and "Sampada" (India) [38,16]. There are different models of gasifier cookstoves in operation in countries such as China and Philippines [47]. Jetter et al. tested some of the popular natural draft gasifier stoves: "Philips model HD4008", "Sampada", and "Mayon Turbo Stove 7000"; and calculate approximate efficiency of 35%, 27%, and 28.5%, respectively [38]. Gasifier stoves generally are quick-heated, energy and emissions efficient, lightweight, portable, and produce biochar. However, gasifier stoves are costly, batch feed, slow to ignite and fuel specific, making them very useful in those situations, but unsuitable in most other places. The gasifier stoves though commercialized, are yet to scale up.

2.2.4. Mono-function versus multi-function cookstoves

A mono-function stove serves a single purpose; such as cooking, water/space heating, fish/meat smoking, baking, milk simmering, grain/flour roasting, etc. Most of the stoves are of a mono function type. Multi-function or multipurpose stoves, apart from cooking, can also serve additional purposes such as water heating, space heating, simmering of milk, fish or meat smoking, roasting and production of light or Biochar. Due to cold weather in China, there exists many ICS for cooking and simultaneous space heating from early stages, for example "Domestic Fuel-Saving Heating Stove" (1991) and "Model LX Cooking/Heating Coal Stove" [48]. Similarly, in cold regions of Pakistan, some cookstoves like "Bukhari", MA-II and I; are in use for cooking and space heating [16].

Champier et al. [49] studied a modern-day multi-function cookstove, coupled with a thermo-electric generator, which will provide light, and electricity for electronic devices, apart from cooking. There is another category of modern-day multi-function stoves: Gasifier cookstoves producing biochar. Biochar is a charcoal-like byproduct of the gasification process, which can increase agricultural productivity by retaining water and nutrients in soil, and protecting soil microbes. Whitman and Lehmann [50] were first to propose the use of cookstoves for the biochar production, as a mean of mitigating climate change. The first-generation pyrolytic cookstoves in Kenya use crop residues, shrub and tree waste as a fuel; and reduce fuel use by 27% over traditional cookstoves, while yielding useful biochar [51,52]. Sparrevik et al. tested TLUD stoves for simultaneous cooking and biochar production, in Zambia [53].

2.2.5. Domestic versus institutional type cookstoves

Domestic cookstove can meet the cooking needs of a family (about five or six members). All the stove models discussed so far are of domestic type.

On the contrary, institutional or community cookstoves serve for large-scale cooking finding application in restaurants, hostels, schools, religious places, etc. Most of the community stoves at present are inefficient three stone stoves. Early versions of community or institutional stoves were "Kesari-200" (India) [54] and "Institutional Coal-Saving Cookstove" (China) [48]. There are many institutional models developed particularly in Nepal, for example, "ESAP Model Two Pot Hole" stove [16]. In India, institutional version of "Oorja" stove suitable for restaurants, canteens and hostels are commercially available under the brand name "Oorja Jumbo" [55]. A large no of the institutional "Rocket" stove are in use in Kenyan schools [56], Malawi [57] and Uganda [58].

2.2.6. Chimney stoves versus stoves without chimney

A chimney is used to remove smoke from the stove combustion chamber and away from the user. Attaching this vertical structure to the stove generally ensures, a rapid air movement through the stove, leading to better combustion and reduced IAP. However, chimney stoves are less efficient, and expensive (due to chimney). In addition, chimney requires maintenance, as blocking of unclean chimney from the soot reduces stove's draft. Monitoring groups in India after some years of stove installation observed, the mean performance of chimney stove "astra" being much lower than expected [59]. Some of the most popular chimney types of stoves are "Uganda 2-pot" (Uganda), "Patsari" (Mexico); "Justa" and "Ecostove" (Central America); and "Onil" (Guatemala) [31,32], most of which are griddle stoves. According to studies by ARC, the chimney-stoves are slower to boil and consume more fuel, although a chimney removes almost 99% of the emissions from the kitchen [31].

2.2.7. Fixed versus portable cookstoves

Metallic and ceramic ICSs suitable for indoor or outdoor movement are portable in nature. In hot developing countries, during summer, cooking takes place in the courtyard to reduce the additional heat from the stove; and in winter, inside the home, to keep the space warm [33]. In Northern India, traditional portable mud stove "Uthaao chullah" is a primary cooking device [33]. All modern ABSs (discussed in Section 2.2.1), such as Gasifier and "Rocket" stoves are also portable in nature.

Most of the mud stoves, multi-pot stoves, and chimney stoves are generally heavier to move; and are of fixed type. Earlier versions of fixed cookstoves were "Abhinav", "Akash" and "Alok" (India) [54]; and "Model PT High-Efficiency Composite Stove" and "Model FL Series Fuel-Saving Composite Stove" (China) [48]. The

recent versions are “Uganda 2-pot” (Uganda), “Patsari” (Mexico); “Justa” and “Ecostove” (Central America); and “Onil” (Guatemala) [31,32]. Fixed type of stoves is further sub-divided based on the number of potholes; examples are single pothole stove, “Grihlaxmi” (India); double pothole stove, “Onil” and “Uganda-2-pot”; and triple pothole stove, “astra” [31,81].

2.2.8. Mud, ceramic, metallic, cement, and hybrid cookstoves

2.2.8.1. Mud stoves. These stoves use local organic construction materials such as clay, sand, mica, straw, grass, sawdust, or dung. Typically, the mixture consists of soil/clay and organic binding material, with dung for extra adhesion. There are many traditional and improved cookstove designs varying in local materials used, number of potholes provided, chimney use, etc. Most of the earliest models from Indian sub-continent were mud stoves, for example “Improved Single Mouth Cooking Stove” (1982-Bangladesh) and “Anagi” (1986-Sri Lanka) [16]. Recent examples of mud stoves are “Improved Clay Stove” (Darfur) [60], “Rocket mud stove” (Uganda) [61] and “mud stove by Escorts Foundation” (Pakistan) [16]. Custom-built mud stoves in India are “Astra” and “Parvati” [62].

Mud stoves are the cheapest type of stoves available, after the TSF. However, mud stoves are insects damage prone, weather, and overfeeding of fuel; hence need higher maintenance, and serve for a lifespan of usually one-two years only [20].

2.2.8.2. Ceramic stoves. Ceramic stoves also use clay, sand, mica, straw, grass, sawdust combined with organic binding materials. The difference in mud stoves and the ceramic stoves is that the ceramic stoves are ablaze in a high temperature kiln resulting in better durability, insulation, and finish. Some examples include the “Mogogo” and “Maendaleo” (East Africa) [60]. All modern ceramic stoves have metal cladding, over the ceramic body, for protection purpose; for examples “Lakech charcoal stove” (Ethiopia) [6], “New Lao Stove” (Cambodia); “Gyapa”, “Uhai” and “Ceramic Jiko” (Kenya); and “StoveTec Prototype Charcoal Stove” [31,61]. Ceramic stoves are more robust than mud stoves, if ablaze correctly. However, Ceramic stoves are costly and difficult to construct than the mud stoves, require maintenance, and have limited flexibility for different pot sizes.

2.2.8.3. Metallic stoves. These are the stoves constructed from steel, sheet metal, or heavy metals like cast iron. The metallic stoves include “Domestic Metal Stove” (Jumla), a special purpose stove designed for high altitude cooking in Nepal; and “Bukhari”, MA-II and I [16]. Some recent metallic stoves include the “Vesto” [60], “Envirofit G-3300 Stove”, “Philips Natural Draft Stove HD4008”, “Berkeley-Darfur Stove”, VITA stove [31], “metallic Jiko” (Africa) [32]; “Vikram”, “Harsha”, and “Magh stove” (India) [63,64].

Metallic stoves are lightweight, portable, quick heating, durable, require little maintenance, and are available in many models in different colors. Disadvantages are prone to corrosion, the risk of burns, and are costliest.

2.2.8.4. Cement stoves. There are many ICS models constructed of cement. Some of the earliest models include “WS Fuel-Saving Composite Stove” from china [48]; and the “Laxmi” stove from India which was originally a mud stove, however, in the later years of the NPIC, cement versions of such stoves were launched; other examples include “Astra” and “Priya” stoves [54]. The “Mirt” stove, made from cement and pumice in Ethiopia since early 1990s, have reported life span of eight years with the fuel efficiency of up to 40% over the TSF [6].

2.2.8.5. Hybrid stoves. These modern prefabricated stoves use more than one type of materials like mud, cement, metal or ceramic. Almost all modern charcoal stoves [6,31,61] and ABSs are of hybrid type where the combustion chamber is of ceramic material, and the outer body is metallic, for example “StoveTec” [26], “Philips Power Stove HD4012” [32], “Oorja” [37], and “Side Feed Fan Stove” from ARC [42].

2.2.9. Fuel wood, charcoal, agri-residue, dung cake and other fuel cookstoves

2.2.9.1. Fuel wood ICS. Wood fuel is the principal source of household energy in developing countries [65]. A majority of ICSs uses wood as a fuel. Widely used stoves in this category is the “6-brick rocket stove”, used in refugee camps in Africa [32]; “WFP Rocket stove” developed by ARC, “Envirofit G-3300 Stove”, “Philips models HD4008 and HD4012”, “Sampada” gasifier stove, “StoveTec Greenfire Wood Stove”, “Berkeley–Darfur Stove” [32,38], and the VITA stove designed by Dr. Baldwin [31].

2.2.9.2. Charcoal ICS. A large fraction of urban populations in the developing countries relies on charcoal for cooking. Africa produces about half of the world’s charcoal, to use as a domestic fuel in much of the eastern and northern regions [5,65]. Some of the countries, like Thailand in Asia, consume charcoal extensively as a household fuel; however, in Latin America, charcoal is not a major household fuel [65]. There are many cookstove models developed exclusively for charcoal burning. Widely used models in Africa are “Kenyan Charcoal Jiko” [38], “Mali Charcoal” (Mali), “Gyapa Charcoal” (Ghana) [31], “UCODEA charcoal stove” (Uganda) and “Lakech” stove (Ethiopia) [32]. Laura Clough [61] tested many African charcoal stoves, to calculate average efficiency of 34%, with a reduction in fuel use up to 71% and in IAP up to 85% (over TSF); though some charcoal stove exhibits a reverse trend.

2.2.9.3. Crop residues ICS. In regions where wood fuel is scarce, crop residue is an important source of cooking fuel. Crop residue includes seasonally available materials like stalk, straw, husk, pod, cobs, shell, and leaves of various crops. There are some gasifier stoves exclusively designed for burning crop residues, like “TN Orient JXQ-10” (China) that burns straw and other biomass residues; rice husk burning stoves like “BMC Rice Husk Gas Stove” (Philippines), “MJ Rice Husk Gas Stove” (Indonesia), “Mayon Turbo Stove 7000” (The Philippines and The Gambia) and “Models 150 and 250” (Vietnam) [47]. “Jinqilin CKQ-80I Stove” from China uses corncobs as primary fuel [38].

2.2.9.4. Dung cake ICS. There are many regions, where people use animal dung as fuel for cookstoves, in absence of sufficient quantities of wood. Cow dung is a major cooking fuel in North India along with agro-residues or fuel wood [63,37], and there exist exclusively dung cake consuming traditional stove for milk simmering, called “Hara” [20]. However, exclusively dung specific ICS has not been designed yet.

2.2.9.5. Miscellaneous and multi fuel types ICS. Some stoves in India, uses loose biomass as a fuel; such as sawdust in “Vivek” and metallic “tube stove”; and leafy biomass in gasifier type “Pulverised fuel stove” [16,66]. Loose biomass is pelletized for use in some stoves, like “Oorja” [37] or briquetted as in Chinese “TLUD Daxu Stove” [47]. China designed a number of coal and coal-briquette burning stoves from mid 1980s to early 1990s [48].

Traditional cookstoves can burn multiple fuels like wood, crop residue and dung cakes. To fulfill the same purpose researchers designed some multi-fuel stoves. Earlier versions of fixed cookstoves like “Abhinav”, “Akash” and “Alok”, (India) were all multi-fuel types of stoves [54]. In modern stoves, “Vesto” (Swaziland) and the “Magh-3G” (India) are designed to burn all types of biomass for cooking [47]. Cambodians use “NLS” (New Lao Stove), originally designed for

Table 1
Additional important information on the cookstove testing protocols.

Protocol and type	Equipments and materials used	Parameters measured	Important parameters determined/ calculated	Salient features
WBT 4.1.2 (Lab)	Weighing scale Thermometer Moisture meter Timer Standard pot(s) Water Fuel Flue gas analyzer	Time Temperature of water, air Air relative humidity Weight of pot Weight of fuel Weight of charcoal + container Local boiling point Dimensions of fuel Wood moisture content Pressure, Hood flow rate CO, PM, CO_2	Fuel consumed Water boiled and vaporized Time to boil and simmer Thermal efficiency Burning rate Specific fuel consumption Firepower and Turn down ratio Net change in char weight Carbon concentration Emissions /liter of water Mass emission factors	• Everything except stove type is under control • Useful for design phase and for stove comparison purpose • Quick, simple and reproducible • Do not predict stove utilization pattern or user satisfaction or adoption of cookstove • Not suitable for predicting performance in rea l household
CCT 2.0 (Lab)	Weighing scale Thermometer Moisture meter Timer Standard pot(s) Food Fuel	Time of cooking Temperature of air Weight of fuel used Weight of pot + cooked food Weight of charcoal + container Local boiling point Dimensions of fuel Fuel moisture content	Weight of food cooked Weight of char remaining Fuel consumed Specific fuel consumption Total cooking time	• Useful for stove comparison purpose • Determines best possible in real households, but not what is achieved in real stove use • Do not predict stove utilization pattern or user satisfaction and adoption of cookstove
HTP (Lab)	Weighing scale Moisture meter Timer Water Different pots Different fuels Flue gas analyzer	Time Temperature of water Weight of water and fuel Wood moisture content CO, CO_2	Fuel consumed, Time to boil Thermal efficiency Burning rate Specific fuel consumption Firepower, Turn down ratio Emissions/liter of water CO/CO_2 ratio	• Test the stoves using the range of pots and fuels • Better to assess different fuel/stove combinations • Not suitable for predicting actual household performance
KPT 3.0 (Field)	Pots and other cooking utensils Moisture meter	Daily fuel consumed Fuel in stock everyday Daily fuel collected Fuel moisture content No of people in household	Daily fuel use Fuel use per capita Daily energy use Energy use per capita	• Useful during actual stove dissemination process • Assess the actual impact on fuel use, stove utilization patterns and user satisfaction • Unable to measure efficiency and cooking time • Uncertain measurements
UCT (Field)	Weighing scale Timer Household pot(s) Food Fuel	Time of cooking Weight of fuel used Weight of pot + cooked food Weight of charcoal Local boiling point Dimensions of fuel	Weight of food cooked Fuel consumed and burn rate Specific fuel consumption Total cooking time Total Energy Consumed Energy consumption rate	• Covers a more no of variables • Quick assessment of single meal stove use • A type of lab test and not totally suitable for real performance check
BCT (Field + Lab)	Weighing scale Thermometer Moisture meter Timer Water, Fuel Flue gas analyzer Emission hood Local pot(s)	Time CO, CO_2 emissions rate Temperature of water Weight of pot, Weight of fuel Weight of charcoal + container Local boiling point Wood moisture content Hood flow rate	Nominal combustion efficiency Burn cycles for daily cooking Fuel consumed Water boiled & vaporized Time to boil & simmer Thermal efficiency Burning rate, Fire power Specific fuel consumption	• Provides opportunities to close the gap between lab and field • Standardized while matching local circumstances
SUMs (Field)	Temperature sensors CO sensors PM sensors	Temperature changes CO concentrations PM concentrations	Stove utilization pattern Emissions pattern	• Able to measure emission & stove utilizati on pattern • Unable to predict efficiency, cooking time, fuel use, firepower and user satisfaction

burning wood and charcoal, for burning garment waste from factories as well [32].

2.3. Supplementary cooking accessories

These accessories improve efficiency and emission performance of an ICS.

2.3.1. Skirts

A skirt is a simple metallic ring that is slightly larger in diameter than the pot, and surrounds it circumferentially. MacCarty et al. in their study on fifty cooking stoves concludes that, the use of a pot skirt can lead to reduction in fuel use and emissions, by 25–30% [67]. However, whether a skirt will be effective or not, is not a straightforward issue. It may be effective under certain conditions, while being ineffective in others, as has

been observed experimentally [68–70]. The famous 'StoveTec' and 'Envirofit' models come with a metal skirts [71].

2.3.2. Haybox or retained heat cookers

Haybox or "Retained heat cooker" is a container insulated with grass, straw, cloth or banana leaves; and has a tightly fitting lid. The use-procedure involves; bringing a cooking pot with food to a boil, and allowing simmering for a few minutes; then taking the pot off the stove, to place it into the haybox to cover by the lid. The insulated and airtight box holds the heat in the boiling pot, and the food cooks without consuming additional fuel. Haybox in addition to providing higher efficiency allows for unattended cooking. Hayboxes are portable, and easy to make. However, it is suitable only for long duration, slow-cooking foods (legumes and grains); and training, and practice are required for successful use. The ICS model "Save80" from Africa, come with a Styrofoam haybox. Don O'Neal [72] has given a detailed guideline of designing haybox or "Retained Heat Cookers".

2.3.3. Customized pots

Customized pot is a pot designed, especially for use with a particular ICS model, to achieve higher energy efficiency. The customized pot maximizes stove performance, at the same time ensuring ease of use. Several special-purpose customized pots like "sloped-sided pot", "finned pot", "super pot", and "Off Fire Reboiling pot" have shown efficiency enhancement along with ICS [60,73–75]. While customized pots increase the heat transfer significantly, the question of making a customized pot at affordable cost remains unanswered.

2.3.4. Thermo-electric generators

Modern ABSs uses a fan that needs a power source, and a promising option is the thermo-electric generator (TEG) (although some stoves use chargeable battery) [37]. TEG is able to harness a stove's temperature gradient, to produce power on demand for fan use; and use a small fraction of the stove's thermal energy for the purpose. An economic analysis indicated a smaller payback period for use of TEG in cookstoves, compared to the batteries [76]. The "Philips Model HD4010" is equipped with a TEG [32]. Several other researchers are working on the development of TEG for biomass cookstoves [77–79].

One of the largest obstacles to the acceptance of clean stoves is that, they do not give off the light unlike traditional stoves; and TEG can solve this problem. Initial testing and calculations by researchers have shown that, the TEG is a feasible and relatively cheap solution for obtaining light from the stove [49,80].

3. Protocols for biomass cookstove testing

Standard cook stove testing protocols are developing from the last thirty years. Testing is helpful for comparing stove models of different genres, gaining in-depth knowledge of the different stove design parameter; and understanding the processes of combustion, fluid mechanics, and heat transfer inside the stove. Theodorovic was the first person, to conduct laboratory tests on biofuel burning stoves in Egypt, in 1954; followed by Singer, in Indonesia in 1961, on the fixed mud stove [81]. To standardize cookstove performance testing methods, the United States Agency for International Development (USAID) arranged a number of workshops, in 1982 [18]. Volunteers in Technical Assistance (VITA) led the efforts, resulting in the three protocols for the cookstove performance testing: water boiling test (WBT), kitchen performance test (KPT), and controlled cooking test (CCT). VITA publication released in 1985, remains the most popular text for cookstove testing, until recently [19]. WBT and its variations have become a well-liked standard for cookstove testing, as compared to the other two. Lee et al. [82] have given a good comparison of these three testing methods, based on different parameters.

3.1. Laboratory tests

Laboratory testing is a type of "Controlled test" [83], intended to provide repeatable and reproducible results. The main characteristics tested in the laboratory are performance characteristics such as combustion quality and emissions, thermal efficiency and heat transfer, power range, safety and durability. Laboratory testing is suitable to identify areas of poor performance, and to determine the effect of a design alteration on the performance. These tests are easier, quicker, and less costly to conduct; however, disclose only the performance of a stove under controlled conditions, and not what stove achieves in real household situation.

3.1.1. Water boiling test (WBT)

This is a lab-based test, designed to explore the basic features of stove performance under controlled setting. It is also useful in the field, to determine whether the stove building is as per design criteria or not. Many organizations all over the world have used revised VITA-1985 WBT protocols, for example, WBT versions of NPIC and NISP [48,54]. The WBT test protocol, which is originally for wood stoves, is also suitable for charcoal stoves with some modifications [31,32,70]. In 2003, WBT was revised to include "Excel spreadsheets" to help users with calculations [84]. Recently, the latest version of WBT, Version 4, was open for public comment, and was still under review. A corrected version of the WBT data calculation spreadsheet 4.1.2 is now available [85]. The WBT protocol consists of the three phases: "High power cold start", "High power hot start" and "Low power". Results from the first two phases are useful to find the difference in stove performance, from the cold and hot start. Similarly, results of last two phases are useful to find the difference in stove performance, between low power and high power operation. Features like simplicity, ease of conduction and quick to do procedures make WBT most widely used testing protocol; accounting for 73% of all the tests performed on cookstoves [86]. However, controlled conditions and performance by trained technicians gives only a gross estimate of actual household cooking, and is not useful to predict field performance. Taylor [87] gives a detailed discussion of the shortcomings of WBT. Table 1 provides additional important information for the protocol.

Jean-François Rozis [88] proposes, "The Comparative Water Boiling Test" (CWBT); a version of WBT modified for the cambodian cooking habits. CWBT aims at duplicating the actual cooking conditions as closely as possible, but is useful only for comparing the fuel savings potential of different cookstoves, under similar-use conditions. CWBT is simple; require minimum equipment, easy to conduct in the field, and use simplified calculations. Two fuel specific versions are available for wood and charcoal.

3.1.2. Controlled cooking test (CCT)

This is an "Efficacy test", [83] to evaluate cookstove performance in a controlled situation, using locally available fuels, pots; and prevailing cooking practices. CCT also takes place under controlled settings to use the stove to its best potential, but while cooking real meals in actual households. The test measures the quantity of fuel used, while the real cook prepares a simple meal on the stove. The CCT is a more suitable lab based stove testing method, for predicting real household performance. The test reveals the best possible performance of the stove in households, but not what is actually achievable in the field. The CCT as well evolved from the previous efforts of VITA International Standards for stove efficiency [19]. However, the modified CCT protocols are now increasingly used for stove testing [46,56,60,71,89–94]. CCT,

which acts as a bridge between WBT and KPT, accounts for 12% of all the tests performed on cookstoves [86]. Table 1 provides additional important information for the protocol.

3.1.3. Heterogeneous testing protocol (HTP)

In real households, the normal practice is to use multiple pot sizes with same stove, and to operate the stove at different firepower as per the cooking needs. However, the use of different pot sizes and firepower variations, which change the flow pattern inside the stove, lead to variations in emissions concentration as well. Hence, the University of Johannesburg, SeTAR Centre, develops a laboratory testing protocol called "Heterogeneous Testing Protocol"; that requires each stove to perform realistic cooking tasks, at three different power levels; using the range of pots and fuels [95].

While testing the same stove with the WBT and the HTP [96], parameters like efficiency and time to boil shows similar results; however, there are fine differences in the objective of the methods. The HTP aims to evaluate the stove parameters, for a range of conditions, whereas, the WBT measures the same parameters, when performing a single task. While testing the same stove by both the methods, the researchers found differences in other parameters such as firepower, fuel burn rate, specific fuel consumption, and turn down ratio [96]. The HTP claims to better assess different fuel/stove combinations, than WBT; however, it is also a type of lab test and is not much popular for stove evaluation [86].

3.2. Field tests

By itself, laboratory testing is inappropriate for verifying real-world performance of cookstoves. Real users do not use a stove in a controlled, repeatable, and reproducible scientific way. In a study on some traditional and ICSs, Roden et al. [97] found that, field measured PM for actual cooking were three times, those measured during simulated cooking in the laboratory. Hence, it is necessary to test a stove in real household situation. Field-testing providing a kind of reality check on the stove performance is an essential requirement of modern cookstove programmes. These "Effectiveness tests" [83] can be extremely useful, mainly in the early stages of stove diffusion. However, such tests are expensive, difficult, and time taking.

3.2.1. Kitchen performance test (KPT)

The kitchen performance test (KPT) is a type of field test, carried out in actual kitchens. Through KPT, researchers assess the actual effect of ICS on household fuel use; and study qualitative stove performance aspects, through household surveys. Researchers conduct KPTs generally during the actual stove dissemination process, with actual users cooking on the stoves as usual. The KPT as well has evolved, from the previous efforts of VITA International Standards for stove efficiency [19]. Since then, it has undergone relatively little change, although efforts are going on to improve the test [81,89,92,93,98]. In a study conducted by Granderson et al. in Guatemalan Highlands, although other studies have shown the "Plancha stove" to be very effective in reducing IAP, the KPT indicates that it offered no benefits with respect to fuel use [99].

KPT, when conducted carefully, provides the best hint of how the stove will perform in the real household scenario. However, it is one of the most challenging ways to test a stove, as it interferes with user's daily activities; and hence used by fewer researchers [86]. In addition, the measurements taken are more uncertain, due to error prone nature of real kitchens conditions as compared to the lab settings.

3.2.2. Stove use monitors (SUMs)

This is a new development, installing electronic temperature data loggers inside the cookstoves, in order to monitor stove use. More increasingly, researchers are also using emission sensors, for monitoring CO and PM. This method is suitable to replace survey methods, for determining reliable estimates of stove utilization. These devices have enabled and simplified; the systematic data collection of the critical stove parameters. SUMs can measure the temperature and emissions concentration changes over a period, store it in the memory of the data logger, and transmit wirelessly. The temperature profile of the cook stove is prepared from the data obtained from SUMs, to establish stove utilization patterns. SUMs are relatively cheap, reliable, accurate, safe, and easy to install and maintain. Using SUMs Zuk et al. studied the impact of "Patsari stove" on fine PM concentrations in rural Mexican homes, and calculated reduction in PM concentrations by 71% near the stove and 58% in the kitchen [100]. A similar study conducted in India, one year after the "Sukhad" stoves installations in Bundelkhand region, identifies a reduction in CO concentrations of 70% and in PM concentrations of 44% [101].

Many types of sensors, including UCB particle and temperature sensors, electrochemical CO sensor, low-cost temperature loggers, LED using sensors, photoelectric sensor; and miniaturized aerosol filter Sampler (MAS) with a cell phone are used as SUMs [33,102–106]. On 9th April, 2010, three companies 'BioLite', "Electronically Monitoring Ecosystems", and "Berkeley Air Monitoring Group", along with the "Sri Ramachandra University in Chennai" (India) secured first place in "The second annual Wireless Innovation Project" by The "Vodafone Americas Foundation and mHealth Alliance" [107]. Although SUMs are getting popular among stove researchers, they can only measure stove utilization pattern and emissions; and not the other crucial parameters such as efficiency, fuel consumption, etc. Burwen and Levine [108] conducted a trial of ICS, in rural Ghana along with SUMs to quantify changes in fuel use, exposure to smoke, and self-reported health benefits.

3.2.3. Uncontrolled cooking test (UCT)

The UCT, which measures performance for single events, evaluates performance of the cookstove for a type of meal, operated according to the locally prevailing cooking practice. Researchers take the readings of fuel used and the food cooked only, while the user prepares a dish of his/her choice. The UCT is a low-cost, rapid, and more cost-effective method, to produce less varied data set than the KPT. However, it is not a widely used field test, by the researchers [86]; however, Robinson et al. conducted 29 UCTs in the rural area of northern Mozambique for wood-burning TSF [109]. The University of Johannesburg, SeTAR Centre, develops the UCT. Compared to CCT, the UCT studies more variables like food type and mass, fuel quantity and its moisture content, cooking time and user's way of operation [109].

3.2.4. Burning cycle test (BCT)

Johnson et al. suggests performance criteria called burning cycle test (BCT), which consists of measuring emission rates and "nominal combustion efficiency ratio" (the fraction of fuel carbon emitted as CO_2), during daily burn cycles in a real household [110]. Subsequently, the BCT involves conducting lab tests; using similar fuel type and composition; to recreate the distribution of emissions rates and combustion efficiencies (and hence the field burn cycles). The protocol is useful to conduct stove testing during the design phase, by comparing alterations with the previous iterations of the stove. The BCT provides opportunities to close the gap between lab and field; standardized while matching local circumstances. BCT assists in promoting development, of stoves with higher combustion and heat transfer efficiencies, while enabling preliminary emissions estimates of greenhouse gases [110].

3.3. Other stove testing protocols

Means [111] proposes a new approach of cookstove durability testing (CDT), to conduct systematic tests under controlled lab-settings and in the field, to predict the life of different stove components under actual use. The CDT proposes to test various physical stove components like grates, coatings, and other metallic parts. Test like CDT, is much required in view of reports, that concern for ICS durability is one of the major reasons impeding efficient adoption of ICS [112]. MNRE India recommends durability criteria for the combustion unit: "to last for at least 10,000 cycles, with a performance degradation of less than 1% per 1000 cycles" [113].

Cookstove safety is another matter, generally not given expected attention. Stoves may possibly cause severe burns, scalds from hot liquids/food, and cuts from sharp metallic edges. In extreme cases, stoves may cause loss of property by setting the house on fire. Initial phases of stove development must eliminate these undesirable possibilities. Johnson [114] has given detailed safety guidelines and testing procedures, for the evaluation of injury risk from a cookstoves; furthermore given are safety ratings for various cookstoves.

4. Comparison of energy and emissions performance for different biomass cookstoves

As already discussed, there are several types of cookstoves available, different in type, construction, principle of operation and performance. Hence, it will be appropriate to compare different stove designs with the help of some common protocol to evaluate relative merits and demerits. For the purpose a biomass cookstove is characterized by the combustion type, fuel type, draft type, combustion chamber type, feed type, use of chimney and that of any type of cooking accessories (as discussed in Section 2.3). In addition, safety ratings and cost of different models are also given in Table 2. These 31 stoves fell under eight main categories: traditional stoves without combustion chambers (TS), wood burning stoves without chimney (WSWC), wood-burning stoves with chimneys (WSC), rocket-type stoves (RS), charcoal-burning stoves (CS), gasifier stoves without fan (GS), gasifier stoves with fan (GSF), and direct combustion forced draft stove (FD).

In Table 3 are given results of WBTs performed on different cookstove models from two different sources. A comparison of results between earlier WBTs performed by these two agencies (EPA and ARC) has shown a good agreement and shown that the results for WBT are replicable for the same stove and fuel tested at different locations [32,67]. Plotting the data collected for different parameters like firepower, time to boil, specific energy consumption, thermal efficiency, CO emissions, and PM emissions; some interesting graphical results are obtained. Following key point are observed from the graphical results obtained from comparison of these 31 cookstoves:

1. Firepower is energy released by fuel combustion per second. Many foods require low power simmering after initial high power boil. More power is required for quick boiling than to

Table 2
Comparative of different cookstoves based on salient features.

Sr. no	Stove type/model name	Combustion type	Draft type	Combustion chamber type	Fuel type	Feed type	Accessories used	Chimney use	Safety ratings	Approx. cost (US$)	Ref.
1.	3 Stone fire	D	N	–	W, O	C	–	–	Poor	–	[31,114]
2.	Mud/sawdust stove	D	N	Mud	W, O	C	–	–	Fair	–	[31,114]
3.	VITA stove	D	N	M	W	C	–	–	Poor	2	[31,114]
4.	Ghana wood stove	D	N	M	W	C	–	–	Fair	5	[31,114]
5.	Upesi portable stove	D	N	Cr	W	C	–	–	–	9.5	[38]
6.	Philips stove HD4008	D	N	M	W, O	C	–	–	–	31	[38]
7.	Berkeley-Darfur stove	D	N	M	W	C	P, S	–	–	25	[38]
8.	Patsari stove	D	N	Br	W	C	–	Y	Fair	35	[31,114]
9.	Uganda 2-pot stove	R	N	Br	W	C	P	Y	Fair	40	[31,114]
10.	Ecostove	R	N	Cr	W	C	–	Y	Fair	67	[31,114]
11.	Onil stove	R	N	Cr	W	C	–	Y	Best	72	[31,114]
12.	Justa stove	R	N	Cr	W	C	–	Y	Good	75	[31,114]
13.	Envirofit G-3300 stove	R	N	M	W	C	S	–	–	31	[38]
14.	StoveTec greenfire stove	R	N	Cr	W, O	C	S	–	–	9	[38]
15.	StoveTec prototype stove	R	N	Cr	Ch	B	P, S	–	–	–	[38]
16.	Mali charcoal stove	D	N	M	Ch	C	–	–	Fair	2.4	[31,114]
17.	Gyapa charcoal stove	D	N	Cr	Ch	B	–	–	Fair	5.9	[31,114]
18.	GERES new lao stove	D	N	Cr	Ch, W	B	–	–	–	3.5	[38]
19.	Jiko, ceramic	D	N	Cr	Ch	B	–	–	–	–	[38]
20.	Jiko, metal	D	N	M	Ch	B	–	–	–	–	[38]
21.	Kenya ceramic jiko	D	N	Cr	Ch	B	–	–	–	6	[38]
22.	Kenya uhai stove	D	N	Cr	Ch	B	–	–	–	11	[38]
23.	StoveTec TLUD stove	G	N	Cr	O	B	S	–	–	–	[38]
24.	Sampada gasifier stove	G	N	M	W, O	C	–	–	–	38	[38]
25.	Philips stove HD4012	G	F	Cr	W, O	C	–	–	–	89	[38]
26.	Wood gas fan stove	G	F	M	W	B	–	–	Fair	99	[31,114]
27.	Belonio rice husk stove	G	F	M	RH	B	–	–	–	40	[38]
28.	Mayon turbo stove 7000	G	F	M	RH, O	C	–	–	–	15	[38]
29.	Oorja stove	G	F	Cr	O	B	–	–	–	35	[38, 46]
30.	Jinqilin CKQ-80I stove	G	F	M	O, W	C	–	Y	–	100	[38]
31.	Wood flame fan stove	D	F	M	W	B	–	–	Best	229	[31,114]

D - Direct Combustion type, G - Gasifier Type, N - Natural Draft Type, F - Forced Draft Type, M - Metallic Chamber, Cr- Ceramic Chamber, C - Continuous Fed, B - Batch Fed, S – Pot Skirt, P – Customized Pot, Y – Chimney used, Br – Brick Chamber, Ch – Charcoal as a fuel, W – Wood as a fuel, RH – Rice husk, O-Other biomass as a fuel, R – Rocket type direct combustion.

Table 3
WBT results for different cookstoves.

Sr. no	Stove type/model name	Fire power (W)			Time to boil (min)		Specific energy consumption (kJ/l)			Thermal efficiency (%)			CO emissions (g/l)			PM emissions (mg/l)			Ref.
		CS	HS	LP	CS	HS	CS	HS	LP[a]	CS	HS	LP	CS[a]	HS[a]	LP[a]	CS[a]	HS[a]	LP[a]	
1	3 Stone fire	7761	8243	3130	24	30	2024	2160	1807	19	20	26	3.635	4.032	7.305	238.2	277.1	215.0	[31]
2	Mud/sawdust stove	7,801	8,004	2,078	18	14	1,293	1,223	1364	28	31	44	2.399	2.228	7.392	265.2	324.8	175.4	[31]
3	VITA stove	8,129	7,944	2,385	14	14	1,122	1,149	1175	29	31	34	3.393	3.622	5.052	283.5	392.2	92.2	[31]
4	Ghana wood stove	6,774	6,207	3,298	24	20	1,619	1,298	1580	24	27	23	3.705	2.441	7.010	653.0	414.9	323.5	[31]
5	Upesi portable stove	5,445	5,489	4,552	29	28	1,959	1,908	3029	22.6	23.8	na	5.485	4.388	6.663	415.3	398.8	351.3	[38]
6	Philips stove HD4008	3,704	3,659	1,923	27	28	1,244	1,263	1219	34.2	34.6	na	0.746	1.895	1.950	344.6	266.5	307.2	[38]
7	Berkeley–Darfur stove	2,668	3,165	2,194	38	30	1,279	1,173	1456	36.1	38.6	na	2.302	2.346	4.222	106.2	144.3	190.7	[38]
8	Patsari stove	8,212	8,439	4,253	40	30	1,869	1,463	2599	20	24	14	1.286	1.083	2.702	71.9	69.3	105.3	[31]
9	Uganda 2-pot stove	6,577	7,580	2,550	19	14	843	759	1475	40	45	33	1.189	1.153	3.284	62.6	72.2	68.2	[31]
10	Ecostove	8,998	9,626	4,531	48	30	5,338	3,642	2989	13	16	16	8.116	4.008	3.546	851.8	642.3	273.3	[31]
11	Onil stove	10,829	10,489	4,796	30	26	1,942	1,474	2592	18	22	13	2.673	1.399	4.267	111.7	112.0	156.6	[31]
12	Justa stove	8,203	8,685	4,180	55	39	2,437	2,006	2493	17	21	14	2.354	1.556	2.870	83.2	78.6	77.6	[31]
13	Envirofit G-3300 stove	4,359	4,864	2,161	20	17	1,047	1,004	1381	38	40.7	na	2.094	2.008	3.591	189.5	195.8	116.0	[38]
14	StoveTec Greenfire stove	3,916	5,054	1,852	24	21	1,182	1,297	1182	35.4	33.1	na	2.364	2.983	2.836	180.8	245.1	148.9	[38]
15	StoveTec prototype stove	2,603	3,999	1,009	33	23	1,042	1,108	623	37.9	34.3	na	5.21	6.87	4.670	151.1	140.7	67.9	[38]
16	Mali charcoal stove	5,859	5,443	2,586	35	43	2,081	2,321	1759	17	18	27	12.7	13.24	9.588	50.2	38.7	7.6	[31]
17	Gyapa charcoal stove	5,790	6,735	3,174	34	23	2,035	1,821	1674	18	19	34	15.58	12.73	12.884	102.5	96.7	17.7	[31]
18	GERES New lao stove	5,864	6,934	1,856	30	14	2,194	1,223	1173	17.8	31.7	na	7.898	8.683	7.743	252.3	143.1	50.4	[38]
19	Jiko, ceramic[b]	3,400	3,299	1,148	30	12	3,185	1,197	2054	13.9	36.6	na	22.3	11.73	18.488	445.9	101.7	135.6	[38]
20	Jiko, Metal[b]	2,724	2,924	1,256	35	16	2,957	1,492	2321	15.1	33.4	na	19.52	13.58	16.944	541.1	59.7	41.8	[38]
21	Kenya ceramic jiko	3,859	3,595	975	38	23	1,830	1,031	610	23.2	31.4	na	12.26	12.48	4.208	194.0	61.9	20.1	[38]
22	Kenya uhai stove	3,332	5,073	1,246	37	19	1,546	1,211	788	27.1	33.1	na	11.44	8.961	5.042	185.5	71.4	12.6	[38]
23	StoveTec TLUD stove[b]	1,375	1,569	1,280	23	18	972	907	2483	52.7	53.8	na	0.486	0.454	2.234	48.6	44.4	77.0	[38]
24	Sampada gasifier stove	5,421	5,626	4,043	23	21	1,533	1,437	2781	26.7	28.5	na	3.373	3.88	3.337	256.0	250.0	378.2	[38]
25	Philips stove HD4012	4,588	5,166	1,696	19	15	1,088	966	1086	36.2	40.5	na	2.285	0.097	0.651	29.4	19.3	29.3	[38]
26	Wood gas fan stove	2,656	2,761	1,400	24	24	755	755	1132	45	46	46	0.549	0.549	0.823	2.2	2.2	3.2	[31]
27	Belonio rice husk stove[b]	1,696	1,447	1,288	16	16	817	703	2174	42.8	49.4	na	6.291	4.921	12.824	66.2	68.2	526.0	[38]
28	Mayon turbo stove 7000	3,748	3,800	3,362	34	35	1,615	1,681	3486	29.3	28.3	na	6.299	6.052	11.851	237.4	216.8	662.3	[38]
29	Oorja stove[b]	1,775	2,565	1,417	32	22	1,717	1,513	2633	32.1	37.2	na	1.03	1.059	11.323	61.8	19.7	194.9	[38]
30	Jinqilin CKQ-80I stove	13,030	10,610	8,008	25	18	3,953	2,315	5809	9.8	17	na	18.97	10.42	20.913	506.0	585.7	1376.8	[38]
31	Wood flame fan stove	4,093	4,003	2,059	20	19	816	856	1266	42	42	42	0.919	0.72	1.022	0.9	6.7	5.7	[31]

All data to boil and simmer 5 l of water for 45 min.

[a] Data presented in the column is taken as it is from Ref. [31], whereas the data from Ref. [38] is modified and converted to equivalent unit from the source data.
[b] WBT conducted with 2 l of water.

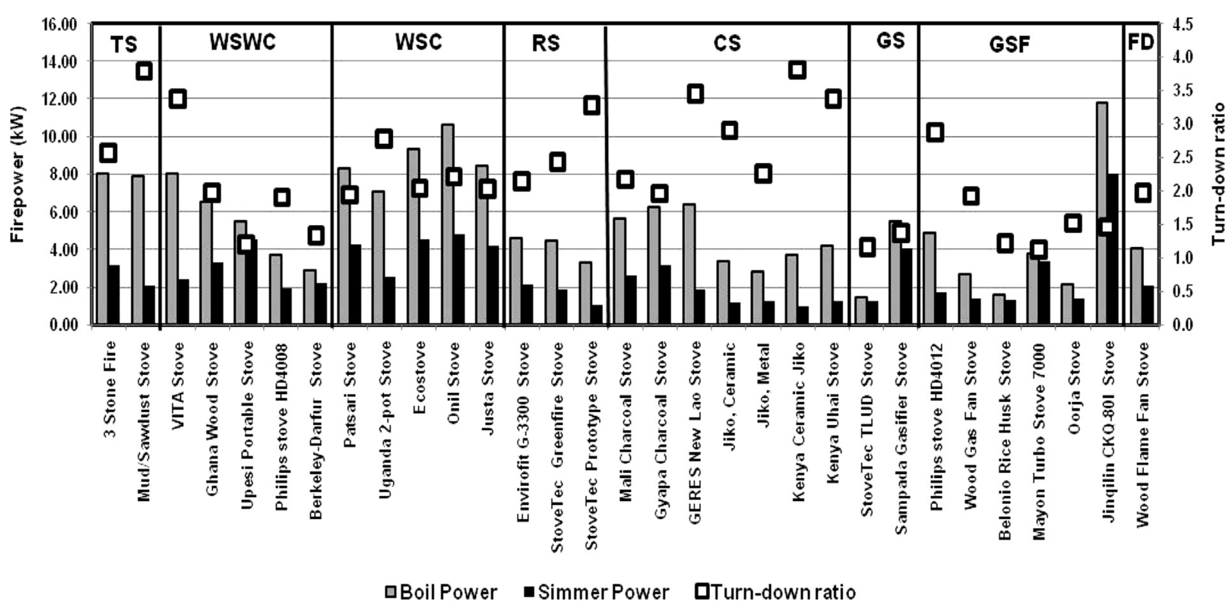

Fig. 3. Fire power and turn-down ratios for different stoves.

simmer. Fig. 3 shows the average boil (high) firepower and the simmer (low) firepower for all the stoves. The ratio of the boil and simmer firepower is termed as the turn-down ratio (TDR), which is an indicator of ability of the stove to be "turned down" from boil to simmer phase, and the extent to which stove firepower can be controlled. A higher TDR means the scope for variation of the stove firepower, if needed. Fig. 3 shows that most of the direct combustion type stoves have TDR more than 6, unlike gasifier stoves with TDR less than 6 for most of the cases. It means that the direct combustion

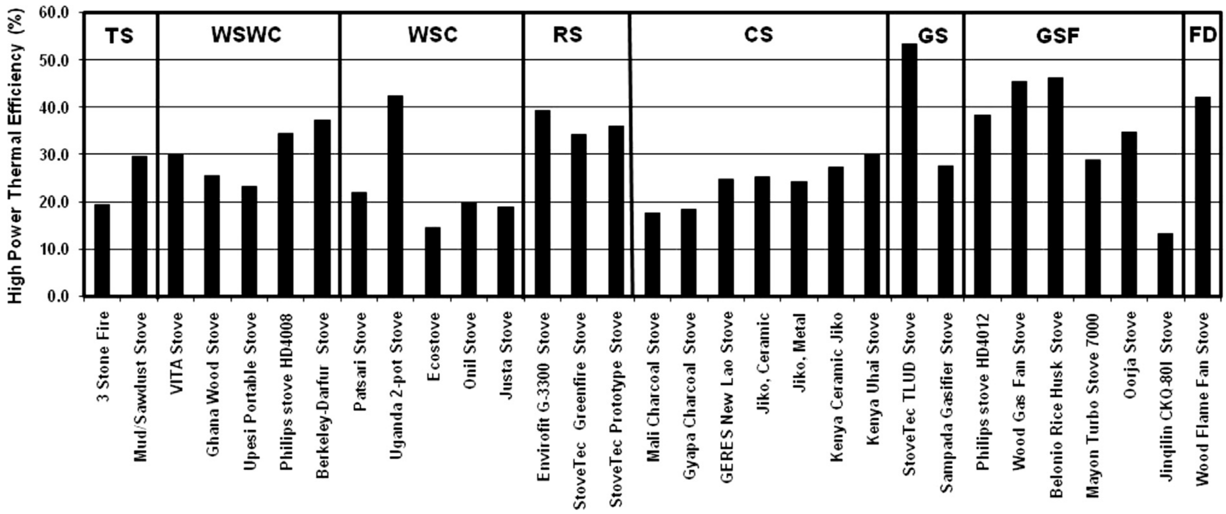

Fig. 4. High power thermal efficiency for different stoves.

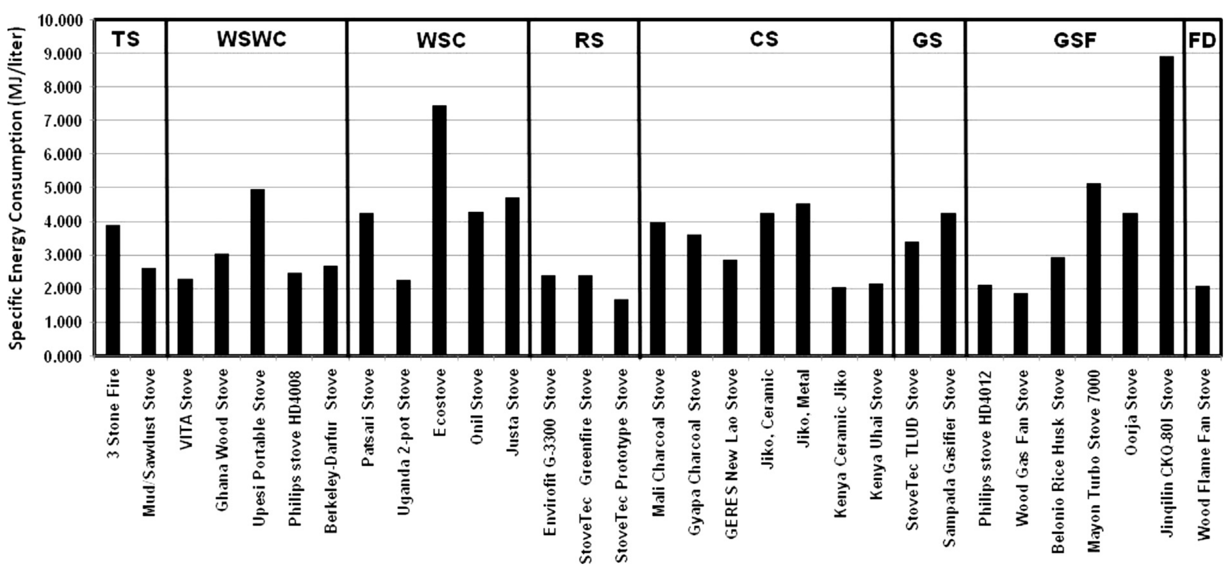

Fig. 5. Specific energy consumption for different stoves.

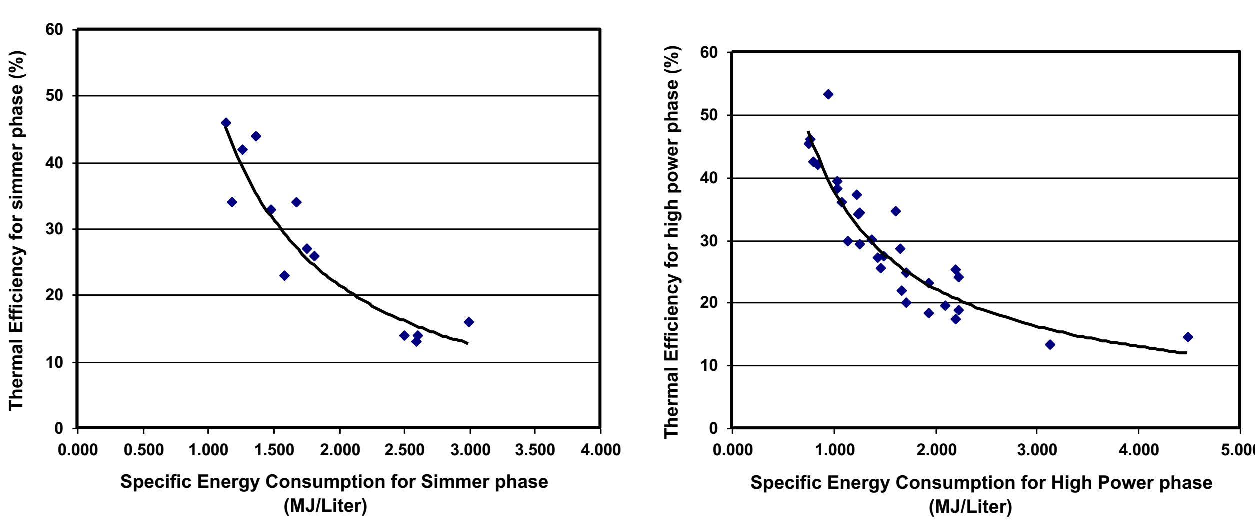

Fig. 6. Variation of thermal efficiency with specific energy consumption.

type stoves will provide better control over fire than the gasifiers will in general.

2. In stove literature, "efficiency" is sometimes a misunderstood word, and it is assumed that high thermal efficiency means low fuel consumption. However, it is only a measure of fraction of fuel energy, which reaches the cooking pot. Interestingly, energy transferred to cooking pot is calculated by measuring the quantity of water evaporated and provides no clue of how much of this is useful for actual cooking process. The basic fact about cooking is a lot of water evaporated by highly efficient stove does not cook food faster than a moderate simmering. Opting for a cookstove based on high thermal efficiency may result in the stove that is not as fuel efficient as possible. An alternative approach called "specific energy consumption" was suggested in 1985 by VITA, Which is the fuel or energy used per unit of food cooked (or water boiled and simmered) [19]. Hence, "Specific Consumption" is the more reliable indicator of stove performance than the "Thermal efficiency". Figs. 4 and 5 shows respectively the high power thermal efficiency and the specific energy consumption for different stoves. Fig. 6 shows that the two stove performance measures are somehow inversely related, the higher efficiency is associated with the lower specific energy consumption; but the agreement in data points is not very high and no linear relationship exists between the two.
3. It can be observed from Fig. 4 that gasifier and rocket type stoves (without chimney) are the most efficient stoves designed so far.
4. Chimney stoves are least efficient amongst all, and some of them are worse than the traditional stoves. Even gasifier stove "Jinqilin CKQ-80I" unlike other gasifiers is having poor efficiency and the probable cause is use of chimney. The other reason for poor performance of chimney stoves is a relatively large amount of thermal mass and resulting low fire temperatures.
5. Again, gasifier and rocket type stoves (without chimney) are least specific energy consuming stoves (Fig. 5). Chimney stoves are showing highest specific energy consumption per liter of water.
6. Here we can make very important observation that puts 'rocket type stoves' ahead of 'gasifier stoves'. If we observe Fig. 5 carefully we can note that rocket type stoves (without fan) are better than the gasifier stoves with fan when it comes to specific energy consumption per liter of water. The high-energy consumption by gasifier stoves during boiling is due to low firepower and low turn-down ratio. Pre-boiling state of the low- power gasifier stoves is longer than high-powered stoves, evaporating more amount of water, which leads to high

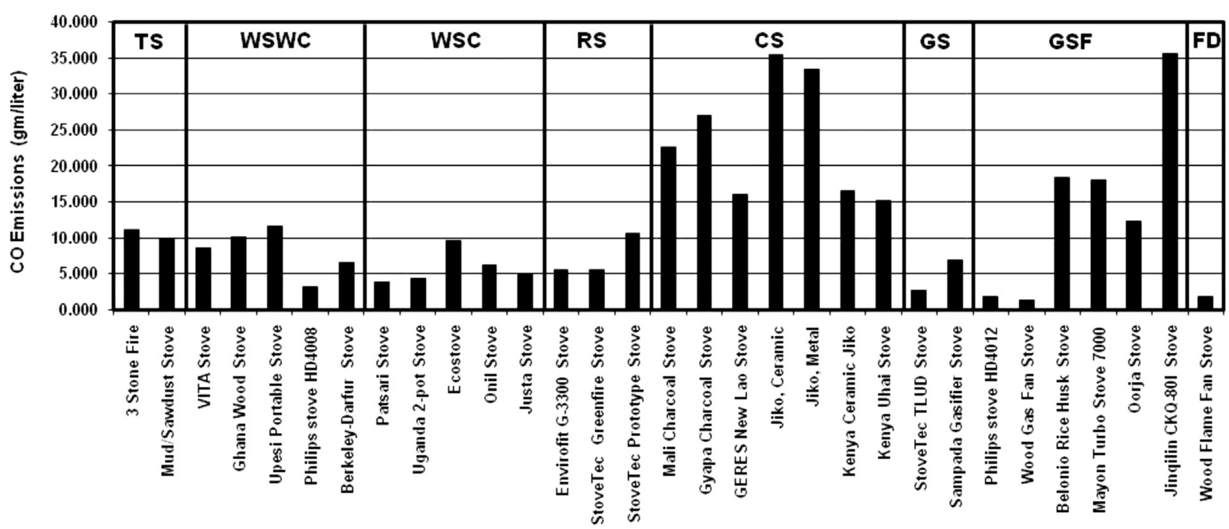

Fig. 7. CO emissions for different stoves.

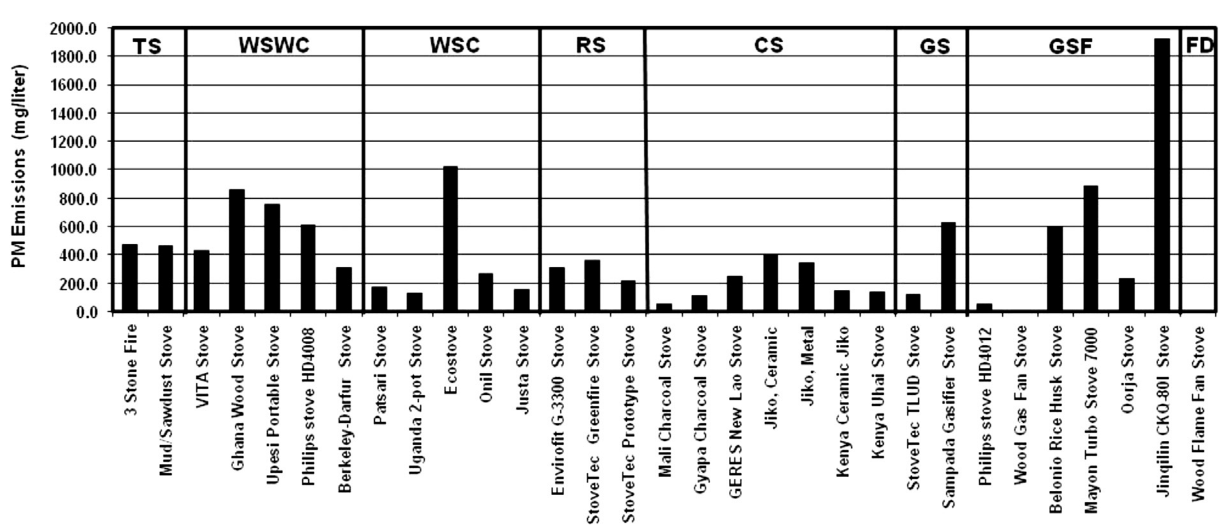

Fig. 8. PM emissions for different stoves.

efficiency (as shown in Fig. 4), although fuel is consumed for a longer period, increasing specific energy consumption.

7. Although charcoal stoves have displayed good thermal efficiency and low specific energy consumption one need to remember that this does not include the energy lost when the charcoal is made from wood. The true energy consumption and emissions of the charcoal stoves should at least double [67], what is measured and shown in Figs. 4 and 5.
8. The fact, which is evident from Fig. 7, is the worst performers when it comes to CO emissions are charcoal stoves; surprisingly followed by many gasifier stoves.
9. PM emissions for charcoal stoves unlike CO emissions are the least amongst all categories as shown in Fig. 8. Charcoal is generally a low-smoke fuel, and hence emits less PM than most of the wood burning stoves.
10. With good turn-down ratio, high thermal efficiency, low specific energy consumption, and lowest emissions, the best stove amongst all is “Wood flame fan stove”. However, it is the costliest stove amongst all.
11. The second best category is “rocket stoves” with all good features along with two of the gasifier stoves “Philips stove HD4012” and “Wood Gas Fan Stove”.
12. The other important fact observed is factory made, mass-produced, quality tested stoves such as “Wood flame fan stove”, “Philips stove HD4012”, “Wood Gas Fan Stove”, “Envirofit G-3300 Stove”, “StoveTec Green fire Stove” are the best on all the fronts. So, it is concluded here that, what affects the stove performance is not only the principle of operation or design of stove, but also the manner in which it is manufactured.
13. Use of a accessories like ‘pot skirt’ and ‘customized pots’ can lead to reduction in fuel consumption as well as harmful emissions.
14. Use of fan (forced air) is found to be energy efficient (Figs. 4 and5), but not necessarily emission efficient (Figs. 7 and 8).

5. Barriers to dissemination and adoption of biomass cookstoves

No ICS programme can achieve its goals unless people adopt and then use the stoves in the long term. While attractive for economic, health, social and environmental perspectives, ICSs need to overcome many barriers to achieve faster adoption rates.

5.1. Institutional barriers

A key factor influencing the implementation of ICSs programme, anywhere, is the existing institutional infrastructure. Important issues are the availability of R&D centers, training venues, technology and information exchange, multilevel monitoring mechanism (certification and quality control), promotional agencies and after sales support and services [10,26,115]. Four types of institutional structures are in existence among the ICS programs: Institution led by a Government agency, NGO/private partnership, semi-governmental structure, and fully commercial private companies. Engaging local government is important, from point of view of general achievement of programme objectives; and has added benefits in policy forming, coordination at the local level, effective awareness raising, and monitoring. Whereas the role of entrepreneurs and NGOs can be helpful in creating awareness, establishing a commercial market and providing after sales support and services. Although the role of local government is important in policy forming, the programmes with the greatest success rate in the past were those, in which the government was not involved in the production or sale of the improved stove [10]. Concentric planning and dependence on multiple layers of bureaucracy have complicated and hampered many programmes in the developing world [10,115].

5.2. Economic and financial barriers

Evidence suggests that, one major obstacle to rapid ICS diffusion is stove price [10,112,116]. Improved cookstoves, which costs \$20–\$85, are typically more expensive than local traditional stoves [117]. Although in the end improved stoves save money, the initial investment required may prevent poor people from purchasing the stove. One of the obvious reasons for the success of China's NISP is its higher rural income and purchasing capacity, than other developing nations [25]. In Ethiopia, higher income increased adoption rates of “Mirt” and “Lakech” stoves [6].

A variety of approaches, such as microfinance services, loans, and financial incentives; are applicable to make household energy technologies more affordable. Originally established for social progression in poverty removal “the microfinance institutions” gives a possible convenient path [118–120]. Microfinance can help to overcome initial investment costs. Furthermore, the marketing channels of existing microfinance institutions are useful for cookstove distribution. Many other potential financing sources such as “Global Environment Facility”, “Climate Investment Funds”, and “International Finance Corporation” are available [26].

Some researchers have argued that, for rapid and far-reaching cookstove adoption, financial incentives for users and manufacturers are indispensable [31,121,122]. However, subsidies are not mandatory for a successful cookstove programme; the best example being China's NISP, where government's financial contribution to the programme was less than 15%; and that as well restricted to “training, administration and promotion” [25]. Evidences from Peru suggest that, providing stoves even free of cost is no guarantee of high use of ICS; for example just 45% of households in 26 villages in Peru, used ICSs that were provided free of charge [123].

The report of MNRE India [113] proposes a concept of continually decreasing subsidies. Gradually decreasing subsidies will make the stoves reasonably priced for the poor, while still providing enough space for commercialization in the long term. The model was rated successful in “Ethiopia's Cooking Efficiency Improvement and New Fuels Marketing Project”, during 1989 to 1995 [113]. Government could provide a small continually diminishing subsidy for the purchase of ICS by the poor people initially; which shall end, once a successful commercial market, creating affordable cook stoves is established. MNRE [113] proposes; region specific, model specific and user-income specific, flexible subsidy structure; with definite end date (with annual assessment and subsidy decrease by 10–20% per year).

Another way of promoting ICSs could be a “conditional cash transfer scheme”. Under a conditional cash transfer program, the government pays a cash amount to the poor households, in exchange of fulfilling certain behavioral pattern (commonly for children's education and health). The conditional cash transfer programme for the initiation of the cookstoves, will pay a small but effective cash amount to the households, for actual stove use. The initiative can attract more people towards ICSs, and will make them accustomed to it. Over a finite time, the user will recognize the advantages of the ICS, and continue the use, even in the absence of any government-aided financial benefits [113].

For the reduction in capital cost of ICSs MNRE recommends a partial or full waver of the taxes on stoves. The report also proposes several other measures like advanced subsidy payment to the manufacturer; micro-credit loans to enterprises, entrepreneurs, and self-help groups, to manufacture/sell cookstoves; and guaranteed advanced purchase of cookstoves for government's own undertakings. Using funds for competence building and motivation rather than subsidizing stoves, would develop a

sustainable system whereby, users will pay the full costs of cookstoves for their own good.

5.3. Policy barriers

Though government assistance in the past, has often done more damage than help in the household energy market, it could play a useful role from policymaking point of view. Several governments provide capital subsidies for competitive household fuels, such as LPG and Kerosene, which leads to price distortion; and needs mitigation [10,117]. In addition, the inappropriate subsidies for the production of ICSs are not useful, as well. Government of India provided a minimum of 50% of subsidy during NPIC directly to the stove manufacturers; hence, the manufacturers never paid attention to the consumer's preferences, which leads to low adoption rate. In addition, the poorly targeted subsidy leads to misuse; a brief account is present in the literature [16,115]. The large subsidy also subdued the commercial sector efforts In India, to develop and manufacture competitive improved stoves [23,115]. Therefore, instead of providing the generous subsidy to consumer, governments can assist in formulating a policy framework, which provides incentives to private sector operators to engage in the production, distribution, and sale of improved stoves. The elements of such a policy framework may include; technical support, training, and assistance in market research as in the case of NISP in China [25,115].

5.4. Social and behavioral barriers

Improved cookstoves do not usually serve the additional local needs fulfilled by traditional stoves such as lighting, space heating, food smoking, repelling insects, drying of a thatched roof, providing a social gathering place and burning multiple fuels [124,125]. When any of these needs remain unfulfilled, and are valued more than the fuel and time saving; ICS rejection occurs. A "very successful stove project" in Ghana, found to be a failure a decade later, as the stoves were not suitable for making the local dishes [115]. In India the "Harsha" and "Vikram" natural draft stoves; while technically inferior, emerge to have more of the desirable stove qualities, expressed by households; as compared to "Oorja" and "Philips" of ABS category, due to existing cooking practices [63]. Developing high-quality cookstoves suitable for mass production is necessary, but users need to be involved in the early stages of the programme, in order to ensure compatibility with local practices.

Women's participation is another essential component of a successful ICS programme. Several researchers have addressed gender issue, in ICS dissemination and adoption programmes. They reiterated that, woman's genuine participation and scope of their income earning opportunities, embedded in the program; is a prerequisite for success [115,126,127].

5.5. Technical and quality related barriers

A study conducted in rural Mexico suggests, "The technology-centered approach" for effective stove dissemination, by evolving better quality stoves [128]. The quality is a very important issue, as evidenced by the low adoption of inferior quality NPIC stoves, not offering the assured firewood savings [11,115]. Nepal et al found that ICS in Nepal as well, do not yield reductions in the demand for firewood [129]. In Peru, cookstove programme suffers due to poor stove quality, lack of expected gains in fuel efficiency, and the difficulty or changes in cooking methods required for successful use [123]. A study in a rural district of the Guatemala observes that, about 67% of "Plancha stoves" in use, developed structural defects [35]. There are several examples cited in the literature, of ICS failed due to technical problems; like a blocked chimney [130] cracking clay liners, mismatch with local pots and other manufacturing/design defects [119]. Many ICS allows use of only certain sizes of fuel wood pieces, thus constraining the choice of fuels [10,32,37].

Another technical barrier is the lack of tools and methods, to monitor and quantify the performance of the ICS in ways that are objective, systematic, cost-effective, and scalable. However, such monitoring of ICS is now getting easier with the new generation of sensors and IT-based SUMs.

5.6. Information and Interaction Barriers

"An alternative theory of technology diffusion" suggests that, the factor that limits the technology diffusion in the society is information; and the consumer already using the technology is the most reliable source of information [131]. In a study conducted in rural Mexico, researchers suggest a "people-centered close interaction approach", as a measure for effective dissemination [128]. In China, women were involved in extensive field-testing and discussions regarding what they wanted in a stove, which can be a major reason for success of NISP [115]. In Guatemala, the follow-up visits and participation of users were instrumental in a successful ICS intervention [127].

In this connection, the performance monitoring of stoves is an inevitable component of any ICS programme, as information related to stove performance is essential for designing next-generation cookstoves. For better technology diffusion, the government can initiate informative programmes; like awareness programmes within communities for fuel resource availability, necessity of sustainable fuel harvesting and benefits of ICS.

6. Road to future

6.1. In-depth engineering analysis for developing new advanced stoves

Because of the presence of the complex phenomenon like fuel combustion, fluid mechanics, heat transfer, and their close interactions; a cookstove is an engineering device that needs multi-faceted treatment. In the summary report of "Biomass Cookstoves Technical Meeting", the expert team stressed for, the improved understanding of fluid mechanics and heat transfer phenomenon occurring inside the stove [7]. Typical cook stoves, including TSF can have combustion efficiencies well above 90%; however, heat transfer efficiencies normally are in the range of 10–40% [13]. Therefore, the heat transfer efficiency is the most important parameter to improve stove performance further. However, increasing heat transfer and overall efficiency, is sometimes at the cost of combustion efficiency; increasing IAP [3]. So it is required to optimize the "holistic" performance of the stove.

Starting with the early efforts of Prasad [12] and Baldwin [9], various researchers performed many heat-transfer studies, identifying number of variables for engineering design of a stove. Important variables are grate area, the shape of the combustion chamber; its diameter, height and volume; bulk flow rate, temperature distribution, excess air ratio, primary to secondary air ratio, fuel dimensions and moisture content, fuel bed height and porosity, effect of the skirt and the firepower [68–70,73,132–136].

Recently, many independent researchers proposed the computational fluid dynamics (CFD) models for the design analysis and optimization of biomass stoves [7,69,113,137–142]. Many modern ABS manufacturers are using CFD and heat transfer modeling, along with rigorous efficiency, emissions, durability testing; for geometry and materials optimization [26]. Miller [141] provides a detailed literature review of, the CFD and heat transfer models applied to

natural convection stoves. Some researchers have used Genetic Algorithms along with CFD, for the stove optimization purpose [142,143].

A committed engineering approach to materials development is must, to balance between the constraints of lower costs and higher performance. Cookstoves require a variety of materials for different components such as the combustion chamber; its insulation and envelope; grate, stand, chimney, and various accessories (see Section 2.3). These materials need to sustain relatively high temperatures, temperature fluctuations, destructive chemical environments, and physical stress. Material considerations for a cookstove include functionality, safety, durability, cost, availability, and manufacturability. The integrated materials engineering approach including the use of experimental data, operating conditions' simulations and computational design tools is required. Specifically, there is a need, to develop systematic procedures and mathematical models for performing "accelerated life-cycle testing", accounting for a wide range of parameters [7]. Good engineering principles along with standard mass production methods, matched by the effective involvement of local artisans and users, are necessary for widespread use of ICS [10].

6.2. Universal stove testing protocol and benchmarking a cookstove

Laboratory tests can enhance stove design, and field tests are important to authenticate real household stove performance. In spite of this significance, a universal standardized stove testing protocol is not yet established. There are some practical difficulties with the existing dominant protocols: unsuitability for batch-loaded stoves, the methodology to determine turndown ratio and, the wide gap between the lab tests and the field tests. The shortcomings of laboratory and field-testing protocols have hindered previous cookstove programmes, as in the "Lorena stove project" from Central America and NPIC in India [87].

A range of tests is likely to be needed to cover all phases of stove design and use, variety of fuels, field conditions, and cooking practices. Recent developments include a new publicly evaluated version of the WBT protocol [84,85]. Johnson et al., as discussed in Section 3.2.4; propose the lab reproduction of the burn cycle, corresponding to the emissions measured from the field; for better stove ability prediction [110]. The debate is still on; whether to judge a stove performance by a single set for efficiency and emissions, at a single power; or a set of these parameters, as a function of the fuel burn rate or input power. Some new testing protocols that evaluate different performance indicators at multiple powers, using multiple fuels, could overcome some limitations of the current framework of laboratory and field tests [95].

"Partnership for Clean Indoor Air" and the "Global Alliance for Clean Cookstoves" jointly organized, "ISO International Workshop on Cookstoves" in February 2012, at the Hague, Netherlands. At the workshop, more than 90 stakeholders finalized and unanimously approved an "ISO International Workshop Agreement" (IWA) [144]. Building on the "Lima Consensus", [145] the IWA provides a skeleton for cookstoves' benchmarking. The IWA proposes "Tiers of Performance" (TOP), for four crucial parameters; like Fuel consumption (Efficiency), Emissions (CO and PM), Indoor Emissions (CO and PM), and Safety [146]. Based upon these different performance indicators a stove receives a rating, somewhere between Tier 0 to Tier 4, "0" being the worst performer and "4" the best. Each stove may have up to four (4) ratings, one each for Efficiency, Emissions, Indoor Emissions, and Safety. The lowest tier from the individual metrics for that indicator decides each of the four ratings. The IWA includes TOP for the WBT 4.1.2 [85] and for the "Biomass Stove Safety Protocol" [114]; and provides a framework to establish TOP for additional test protocols. The "Workshop" recommends that, in the future, protocols based on appropriate performance indicator need to develop for durability and emissions (both health and climate related). The IWA, also recognizes the failure of the laboratory testing in fully reflecting field performance, and recommends the inclusion of the factors in future developments. Starting with Tier 0 for TSF, the performance results of emissions and efficiency for the majority of the ICSs put them in Tiers 1 and 2. Only the ABSs like Fan stoves and Gasifier stoves are rated as Tier 3 or Tier 4 cookstoves [38,86].

6.3. Commercialization of cookstove technology

The failures of government and charitable efforts, at the large-scale sustained adoption of ICSs, shifted the focus on commercial and market driven approach. The most successful stove programme to date; China's NISP combined a central thrust with locally coordinated efforts, to create a sustainable commercial market for stoves [25]. Similarly, NGO funding in the early 1980s developed the "Kenya Ceramic Jiko" charcoal stove, but over time, the stove production gets commercialized; which has seen wide success with 2 million stoves in use as of 2002 [117]. Another successful cookstove commercialization programme is of "Anagi" stove in Sri Lanka, currently in use at 30% of urban and 23% of rural Sri Lankan households, with the number of stoves reaching 3 million [147]. Commercialization of "Anagi" takes a time span of about three decades in four distinguishable phases. First stage included stove design and testing in coordination with the NGO, followed by a second stage of large-scale dissemination ultimately ending in market's collapse, but still resulting in awareness raising. Third stage, learning from the second stage adopted appropriate stove design and commercialization strategy. Finally, the diversification stage with de-centralize technical expertise and dissemination reached rural poor. In Rwanda, alterations made in response to users' feedback on the stove's size, quality, color, type, and door construction; made the commercialization possible, off-course high charcoal prize being another major reason [10]. These cases suggest commercialization and not the charitable efforts, as the solution to ICSs dissemination barriers.

The essential ingredients of a successful commercialized stove programme are: uninterrupted programme through different phases, sharing global experience with local entrepreneurs; involvement of Government, semi-government, NGOs and finally private sector in transitioning to a commercialized market; adequate market research, consumer responsive product design, field monitoring and appropriate customers targeting [10,11,115,25,113,117,147]. Though the recent developments in ICSs are encouraging, the larger-scale adoption and commercialization is not an easy task. Major barriers involve high costs; low income of potential customers, and hence low profit margins; high marketing and promotional costs, limited market research, large regional differences in cooking practices, low cookstove acceptance and adoption, lack of awareness for health and environmental benefits, limited available financial sources, and subsidized price of alternative household technologies [117,122,147].

However, new sources of the Carbon finance from CDM can stimulate large-scale adoption of the ICS, by reducing the stove purchase price, as in the case of "Ugastove" in Uganda [27,148]. Stringent monitoring practices mandatory during the crediting period of the Carbon projects, are also supportive of long-term sustainable use of cookstoves.

7. Proposed modern cookstove design methodology

7.1. Important considerations in modern cookstove design

There are three major considerations while designing a cookstove: technical, social and economical. Social considerations depend upon prevailing cultural and local needs and constraints, and are a prerequisite for long-term adoption of a cookstove by the society.

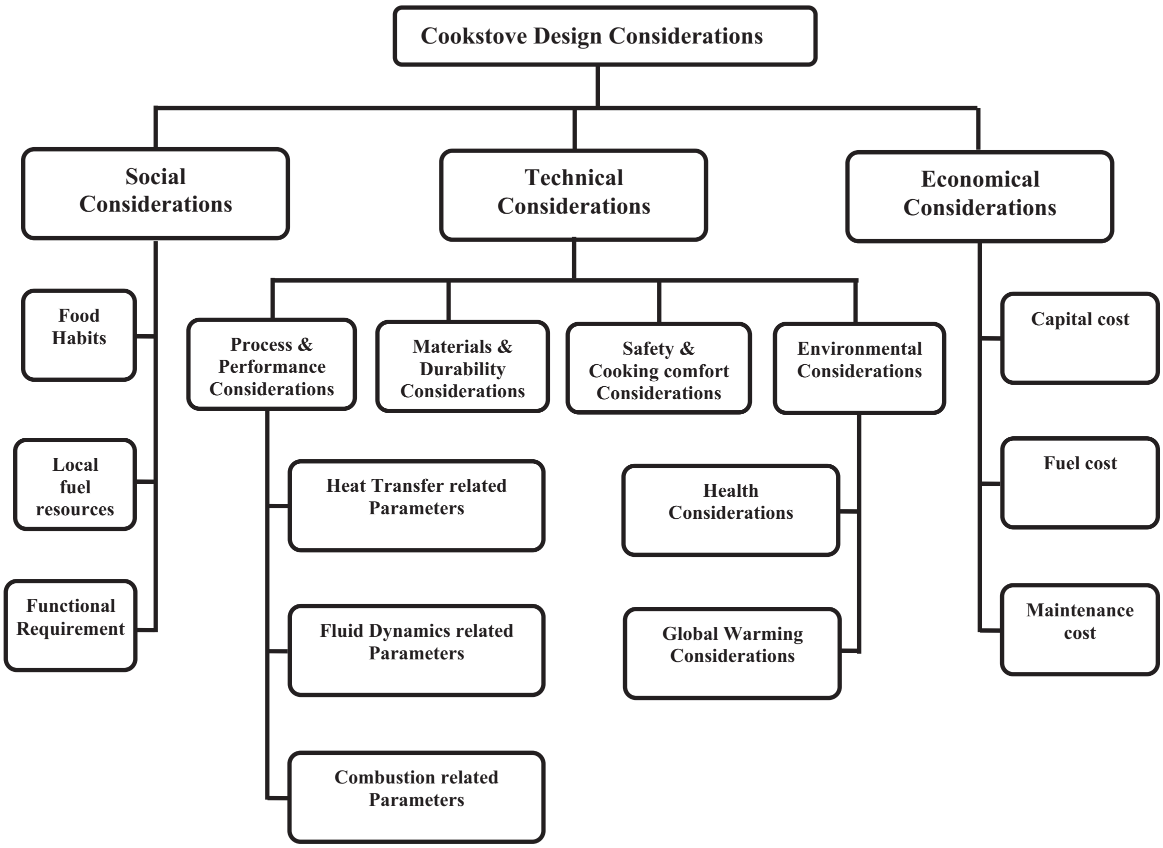

Fig. 9. Important considerations for cookstove design.

Technical considerations such as high efficiency, low emissions, material durability, and user's safety are at the heart of the current R&D activities in cookstove design. Finally, cost effectiveness determines the pay back period of the investment, and therefore is very important for successful cookstove dissemination. Although classified in different categories most of the major and sub criterion mentioned in Fig. 9 are dependent on each other. For example, technical and economical considerations are inseparable, as the cost effectiveness usually depends upon the technical performance of the stove.

7.2. Proposed systematic approach for modern cookstove design

Different cookstove models can have different requirements; and hence different design considerations as described in previous section; however, a standard systematic approach to cookstove design is highly desirable. While the technical studies discussed earlier provide some insights in cookstove design, none of them presents a systematic approach to achieve the solution appropriate for the given situation. Hence, a "Nine-step standard systematic approach for modern cookstove design" (Fig. 10) is proposed (major activities involved during a particular step are also listed side by side):

7.2.1. Problem identification and definition

The first step in any design process is the identification of need or existing problem. In case of the cookstoves the user's needs as per prevailing food culture and local environment shall be studied in depth, for example local food habits, cooking practices, functional requirements of stove, fuel type in use and its consumption, conventional pot size/shape, climate type, and user's future cooking aspirations. A survey for collecting information related to the site and the households is recommended for building the 'targeted consumer' profile. To this can be added engineering aspirations on the basis of the worldwide stove-research outcomes; such as fuel saving, cleaner indoor atmosphere, environmental damage mitigation, use of alternative biomass fuels, lower house-fire risk and burns, cooking comfort and durability of the stove. Socioeconomic aspirations such as generation of employment and consequent income from stove manufacturing, sales and after services, reduced risk of gender-based violence can be included.

7.2.2. Problem analysis

The aim of analysis phase is development of a workable and well-defined design space for the problem, within which one can scientifically search for the solution. The problem is tried on technical, social, and economical front at a go. Technical parameters to quantify at the end of problem analysis are power output of the stove, cooking time for targeted energy output, targeted specific energy consumption, efficiency, and emission levels. Socially or culturally related parameters to settle are preferable fuel and pot type, preferable dimensions for ensuring cooking comfort (diameter, height, pot to top distance, ground to bottom clearance), standard stove operating procedures and practices. Problem analysis also includes the market research and economic feasibility analysis. The information regarding initial cost, market demand, consumer expectations, and type of the targeted application (domestic/commercial/institutional) must be collected through inputs from users' community, individual consumer surveys, communication with similar sales organizations and product outlets. Economic feasibility analysis must be carried out, taking in to considerations capital and running cost, subsidies available (if any), possible financing sources, cost of competitive technology and estimated savings due to use of the improved stove; to calculate payback

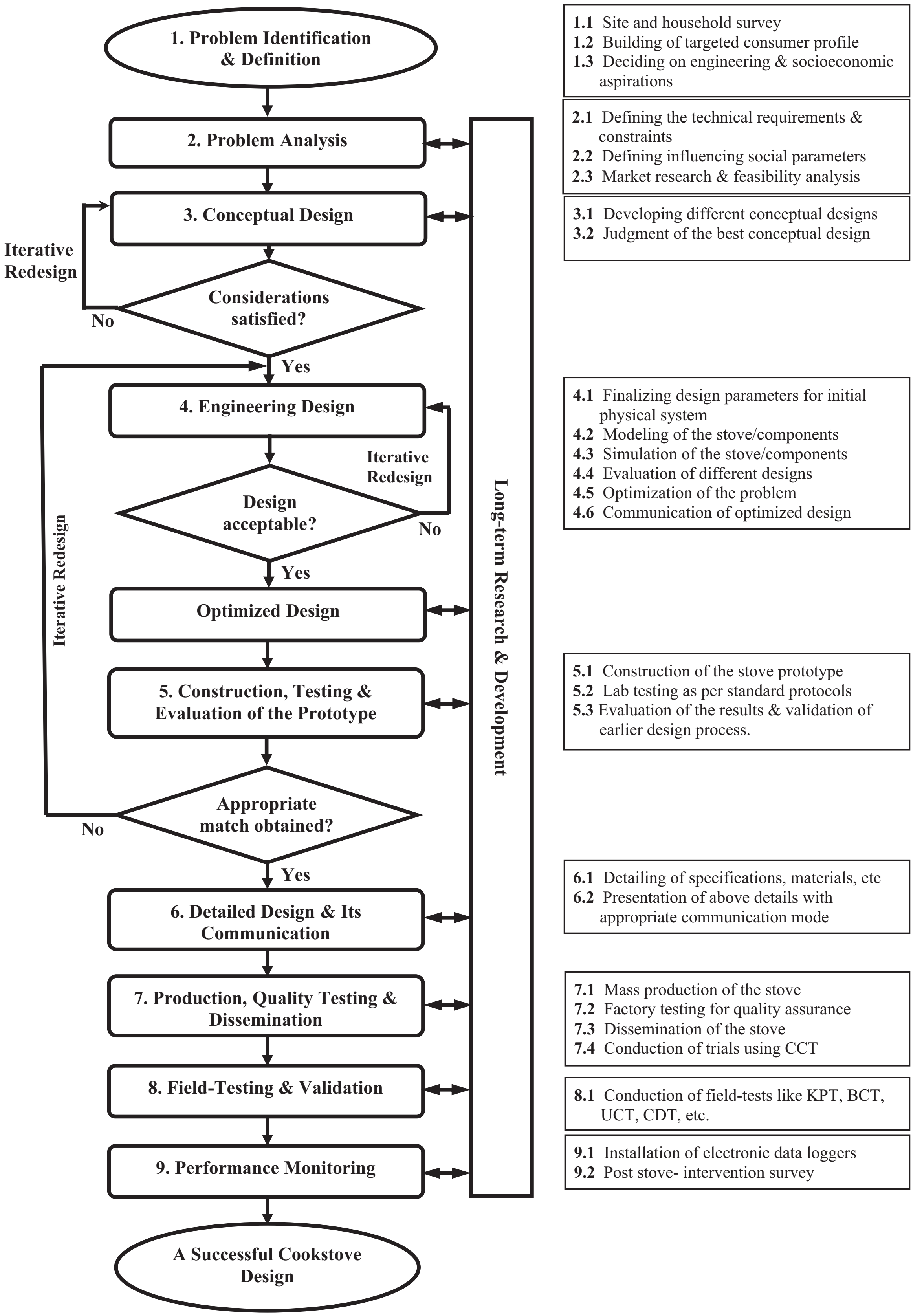

Fig. 10. A systematic approach for cookstove design.

period of the investment made. The problem is finally stated in the form of a quantified and qualified set of technical, social, and economical requirements and/or constraints.

7.2.3. Conceptual design

Based upon the design space defined in terms of requirements and constraints, a stove researcher must develop different design

alternatives catering to the need or problem. These designs may include modification of existing popular stove design, recombination of different stove designs, or full product design from scrap. Having developed apparently feasible ideas for solving the problem, these ideas must be reduced in number, based on the requirements and constraints as developed earlier. For the purpose, these collective requirements and constraints are classified as 'Necessary considerations' and 'Adjustable considerations'. 'Necessary considerations' includes rigid-constraints such as the locally available fuel resources and prevailing cooking practices; and mandatory requirements such as the local and international benchmarks for emissions, efficiency and safety (discussed in detail in Sections 3 and 6.2). 'Adjustable considerations' such as appearance, provision of heat regulation, durability, and maintenance requirements can be relaxed, if demanded by the better complementary considerations. A preliminary stove design that does not comply with the 'Necessary considerations' shall be rejected or modified; however, design can proceed even by partially fulfilling the 'Adjustable requirements'. Deciding the final concept shall be typically a group decision made by researchers and consumers through a continuous dialogue.

7.2.4. Engineering design for best possible solution

The next stage is to use fundamental and applied principles of science and engineering to generate valid solutions for the chosen conceptual design, while focusing on the quantitative as well as qualitative aspects. Mostly what we have in the name of engineering analysis is empirical correlations developed by earlier researchers; however, modern analysis tools such as mathematical modeling of different physical phenomenon, dimensional analysis, energy and exergy analysis, numerical simulation, and CFD simulation are increasingly used. These modern tools are necessary for having insight of stove function and establishing qualitative trends for the variation of different parameters within stove. However, general design principles developed by earlier researchers such as introducing a grate below the fuel bed, controlling combustion air flow, preheating of incoming air, heating and burning the tips of the sticks only, maintaining constant cross-sectional area throughout the cookstove, provision of a good insulation to the outskirt of the cookstove must be followed wherever possible [149]. All the technical consideration shown in Fig. 9 usually form part of the engineering design process.

The first step in the engineering design is finalizing design parameters for 'initial physical system'; such as fuel type (processed or unprocessed), combustion type (direct or gasified), and heat transfer type (forced or free). The next step is to model and analyze various components of the stove. Modeling of the stove components is a process of formulation of mathematical equations applying the basic conservation equation, which governs the behavior of the actual stove component.

The next step is simulation; the process of subjecting an individual stove component model or combined stove model to various boundary or operating conditions, to determine their behavioral characteristics. Numerical methods are used most of the times to solve the equations obtained from modeling, particularly the nonlinear partial and ordinary differential equations frequently appearing in stove design. Next step is obtaining the discretized equations using the numerical methods such as the FDM and FVM for execution on the computer, yielding a numerical model, and subjecting it to different design variables values, across the range decided by the constraints. The numerical models are executed on computers due to the presence of complexities in the governing equations, several combined submodels for the different stove components, complicated geometry, and complicated boundary conditions. The integration of empirical correlations, material properties, and experimental data increases complications further.

An acceptable design, which satisfies the given stove requirements without constraints violation is chosen. Therefore, the simulation results are compared with the problem statement to determine if acceptability of a particular design. If the design violates the constraints or does not fulfill the requirements, a different design is selected, simulated, and evaluated. The process is repeated until one gets an acceptable design.

Now a day, it is equally essential to optimize the stove design, which while contenting within the constraints forced by efficiency, emissions, economics, safety, and other related considerations; will perform the task in desired manner. Optimization involves maximization or minimization of a chosen variable (the objective function) related to quantities like efficiency, specific consumption, heat transfer, emissions, cost etc. The acceptable designs are subjected to optimization to satisfy the given stove requirements and constraints. Depending on the available form of the simulation results, various optimization methods are applicable. However, the most popular algorithm for the stove purpose is Genetic algorithms which mimic the process of natural selection and survival of the fittest and is well suited for evaluating non-linear search spaces frequently involved in stove design. A sensitivity analysis can also be performed. In addition, technical and economical considerations are carefully included to settle tradeoffs, to obtain the final design. The last step in the engineering design process is the design specifications communication for fabrication and prototype development.

7.2.5. Construction, testing and evaluation of a prototype

Prototyping involve building either full-size or scaled model of the stove to evaluate further the merits of the design. All the scientific methods mentioned in the previous phase require validation by experimentation on the complete physical prototype or separate simulation models for different phenomenon/components (if required). In addition, to judge stove performance, laboratory testing of the prototype is must. Testing ensures that the stove meets recommended global and local benchmarks (discussed earlier in Sections 3.1 and 6.2). Testing is also important for validation of results obtained by earlier stages like mathematical modeling, numerical simulation, and optimization. Simulation accuracy can also be estimated by making comparison between the simulation results and experimental data. Therefore, it is important to obtain an accurate linkage between the mathematical model and the actual stove prototype. It helps in discovering the possible problems in the stove design before mass production and matching the stove-characteristics such as appearance, materials, and performance closely with the consumer expectation. If a very bad match is obtained with earlier results, the whole process of engineering design may be reiterated using inputs from experimentation. The process keep on repeating, reiterating, re-specifying, and re-designing until a good match is obtained between mathematical and experimental results.

7.2.6. Detailed design and its communication

Detail designing is process of developing micro-specification of all the components of stoves (combustion chamber, walls, insulation, grate, pot type/geometry, control mechanism, skirt, customized pot, fan, TEG, inbuilt temperature/emission sensors, etc). Detailed design may include overall geometry and configuration of the stove, list of different components of stove, chosen materials for each component, particulars of different components, ranges of operating cooking conditions and power requirement.

These details can be communicated using engineering drawings (for dimensions and tolerances), specification sheets, and computer-aided design (CAD) software. Results for numerical simulation and prototype testing can also be included as charts and graphs. A detailed report must be prepared for all the activities carried so far. The information must be supplied in

sufficient details so that the fabrication facilities can proceed for production of the stove. It may include suggestion on manufacturing processes suitable for different components of stove also.

7.2.7. Production, quality testing and dissemination

The next step is obviously factory production of the stove based upon the design details obtained from the previous phase. Quality assurance is an integral part of any manufacturing process now a day and hence the stove must be extensively tested over the expected range of cooking conditions. Reliability of the stove over its life span can also be assessed by conducting 'accelerated tests'. These tests verify and ascertain the design specifications, while ensuring the satisfactory stove performance; validate and improve the earlier model of the stove; establish safety levels during cooking, and help to obtain the stove performance characteristics. Based upon the actual measurements these tests are useful for iterative improvements in the stove design. Finally, the stove can be disseminated through different governmental, non-governmental, and private agencies. Various activities involved in the process of dissemination are advertising in different media, demonstration of the stove functioning to consumers, conduction of CCT to evaluate stove performance in actual kitchen under controlled conditions, installation at site if required, training to stove operator to maximize gain and sales through different channels.

7.2.8. Field-testing and validation

As discussed earlier (Sections 3.2 and 6.2) laboratory testing is inappropriate for verifying real-world performance of cookstoves, and hence field-testing for verification of laboratory and factory claimed performance is must. Standard protocols like KPT, BCT, and UCT can be used for the purpose. A useful feedback can be provided to iterative design process from these field tests.

7.2.9. Performance monitoring

This includes installing electronic temperature data loggers and emissions sensors inside the cookstoves (inbuilt or site installed), in order to monitor stove use by the consumer. This is an important step for systematic data collection of the critical stove parameters and determining reliable estimates of stove utilization pattern. At the end of the programme period, the post-intervention survey is recommended, in order to gain information on realistic scenario of the stove use impact. Stove performance can also be monitored parallel to after sale services such as repair and maintenance.

Finally, a stove model like any other product must go through continuous design iterations, to satisfy consumer's need over a long term. For long-term sustainable adoption of cookstoves, use of key learning from all nine steps in iterative manner is necessary. Often, the technical information necessary for engineering design of a new stove model is not available, and can be obtained from the literature on relevant stove processes and components. The research and development database interacts with entire design activities as shown in Fig. 10, and supply various inputs across different stove development stages. Efforts are made by earlier to the present-day researchers to store and provide free access to the cookstove research activities literature. Database by ARC, and "Household Energy, Climate, and Health Research Group", At Global Environmental Health, University of California, Berkeley are two biggest sources for stove research documentation.

8. Conclusion

About half the people across the world use different types of biomass fuels, to cook a large number of dishes in diverse ways. Furthermore, adoption and sustained usage of stoves is a complex, multi-stage process, in which more than one device is routinely used, a practice sometimes called "stacking" [8,128,148]. Hence, a large number of stove designs are required to meet the diversity of fuels, pots, foods, cooking methods, price-points, and aesthetics. We cannot force the new stoves upon the consumers; they must be clearly better than the current cooking practices that users switch to it on their own. It is essential to sell well-fabricated, good quality, inexpensive stoves, with prompt after-sale services. Today's modern generation stove, manufactured completely in factories, after adequate market research, based upon technically optimized designs, and rigorous quality control assurance is a new ray of hope. In many studies, these factory-manufactured stoves have proven their superiority over traditional or artisan-built stoves [71,91]. Commercial cook stove operations worldwide has demonstrated ability to scale up, proving that the financial sustainability with adequate profits is possible, in case of ICS enterprises [37,117].

Scientific principles of combustion, fluid mechanics, and heat transfer are already under study, but require further integration. We need experimentally validated user-friendly mathematical and computational tools, to go beyond empirical methods. Finally, we need to focus on developing the cookstove technologies to publicize, how close we imitate the performance of LPG (the most aspired cooking-appliances); off-course with biomass fuels, whether unprocessed, lightly processed, palletized or briquetted [150].

Lastly, only affordable and technically optimized stoves are not enough to create acceptance in the society. We need to identify and unite; the decisive socio-cultural, natural, and local resource conditions, with economics and modern technology. The building blocks of the successful ICS program identified from this review are research and development, universal testing standards and benchmarks, monitoring mechanisms; involvement of private-sector interest, supported by governmental institutions; innovative financing models and sources, and collective effort of the enthusiastic stakeholders. All of this is essential, if we want to deploy hundreds of better stove models to millions of poor people.

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